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WATER RESOURCES ACTIVITIES IN THE UNITED STATES. WEATHER MODIFICATION: PART I. PROGRESS AND POSSIBILITIES IN WEATHER MODIFICATION. PART II. WEATHER MODIFICATION AS A NEW TECHNIQUE TO INCREASE WATER SUPPLIED

A. M. Eberle

Select Committee on National Water Resources, U. S. Senate

January 1960

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86th Congress
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COMMITTEE PRINT NO. 22

WATER RESOURCES ACTIVITIES IN THE UNITED STATES

WEATHER MODIFICATION

SELECT COMMITTEE ON NATIONAL WATER RESOURCES
UNITED STATES SENATE

PURSUANT TO

S. Res. 48

EIGHTY-SIXTH CONGRESS

JANUARY 1960

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SELECT COMMITTEE ON NATIONAL WATER RESOURCES

(Pursuant to S. Res. 48, 86th Cong.)

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STATEMENT BY THE CHAIRMAN

DECEMBER 29, 1959.

To the Members of the Senate Select Committee on National Water Resources:

Senate Resolution 48 directs our committee to give attention to the character of legislation that may encourage the adoption of new technical methods and improved processes for increasing the usefulness of available water resources, including, among others, weather modification. Authorities have estimated that in an average year about 4¾ billion acre-feet of water falls on the United States in the form of precipitation. It has been estimated that only 5 to 15 percent of the available moisture in a cloud system reaches the ground during a rainstorm. It is obvious, therefore, that even a slight increase in the efficiency or amount of precipitation could have a tremendous effect toward increasing our water supplies.

Many studies of weather modification have been undertaken in recent years, most notable of which is that of the Advisory Committee on Weather Control which reported to the President on December 31, 1957. By Public Law 510, 85th Congress, approved July 11, 1958, the National Science Foundation was assigned responsibility to keep up with work in this field and to report annually to the Congress. The first of these annual reports is to be made in January 1960, and it should be of great interest to the committee.

There has been a tremendous amount of information developed in this field in recent years, and in order that we might have a report more directly related to the committee's activities, I asked the Weather Bureau of the U.S. Department of Commerce to prepare a report for the committee covering all aspects of the field of weather modification in relation to water resources, and to give its views on means of assuring the most rapid progress in this field as a way to increase the usefulness of our available water resources. In addition, the Public Works Committee of the Senate made available the services of Dean A. M. Eberle, a former member of the Advisory Committee on Weather Control, and he agreed to prepare independently a summary report and recommendations covering the field of induced precipitation as a means of increasing our water supplies.

These two reports indicate that there are tremendous possibilities for increasing the availability of water supplies in the United States if man is able to unlock the secrets of nature with regard to precipitation and turn them to beneficial use, and contain suggestions as to what actions should be taken next.

These reports will be of great interest to you, to the other Members of the Senate, and to others concerned with finding solutions to the Nation's water problems. Therefore, I am having them printed in one of the series of committee prints dealing with aspects of water resources activities which are being considered by the committee.

ROB'T S. KERR, *Chairman,*
Select Committee on
National Water Resources.

COMMUNICATIONS

JULY 13, 1959.

HON. FREDERICK H. MUELLER,
Acting Secretary of Commerce,
The Department of Commerce, Washington, D.C.
(Attention of Mr. Francis W. Reichelderfer, Chief of Weather Bureau.)

MY DEAR MR. SECRETARY: Further reference is made to my letter of June 15 concerning the work of the Select Committee on National Water Resources. One of the subjects to which the committee has been directed to give attention by the provisions of Senate Resolution 48, is the possibility of increasing the usefulness of available water resources through weather modification.

The committee is impressed with the capabilities of the staff of the Weather Bureau and believes that that agency would be extremely well qualified to discuss and comment on all aspects of the field of weather modification. Accordingly, it is requested that a report on means of assuring the most rapid progress in weather modification be prepared by the Weather Bureau.

The principal objective of the report is to inform the committee as to what might reasonably be expected in the field of weather modification as a means of increasing the availability and usefulness of the Nation's water resources in meeting future needs. The report should contain a description of weather modification techniques with emphasis on progress in this field since the compilation of the report of the President's Advisory Committee on Weather Modification in 1957, changes in the outlook for application of weather modification techniques in the United States since that time, and discussion of what may be expected to develop in this field between now and 1980 under present conditions.

The report should also discuss recent foreign developments in weather modification and possible means and measures which might be considered to encourage the most rapid further progress in weather modification.

The committee would expect the Weather Bureau to secure the cooperation of and cover the work being done by the National Aeronautics and Space Administration, the National Science Foundation, and the Department of Defense.

We would like this subject to be covered in a summary report of not more than 10,000 words, with whatever tables, charts, appendixes, and graphic illustrations as may be considered necessary. It would be most helpful if this information could be furnished the committee by October 1, 1959.

The committee is also having a report on this subject prepared by Dean A. M. Eberle, formerly a member of the Advisory Committee on Weather Control, and we would appreciate your cooperation in furnishing him with any information which he needs and which the Weather Bureau may have in this field.

The committee staff will be glad to discuss any problems which may arise in the preparation of the report with representatives of the Weather Bureau.

Sincerely yours,

ROB'T S. KERR, *Chairman.*

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THE SECRETARY OF COMMERCE,
Washington, D.C., October 30, 1959.

Hon. ROBERT S. KERR,
Chairman, Senate Select Committee on National Water Resources,
U.S. Senate, Washington, D.C.

DEAR SENATOR KERR: Your letter of July 13 requested the Weather Bureau to prepare a report on the possibilities of available water resources through weather modification. The report is enclosed herewith. Additional copies will be furnished by the Weather Bureau.

We appreciate the opportunity to present information on this important subject. If additional comments are required from the Weather Bureau we shall be glad to be informed.

Sincerely yours,

JOHN J. ALLEN, JR.,
Acting Secretary of Commerce.

CONTENTS

	Page
Statement by the Chairman	III
Communications	V

PART 1

PROGRESS AND POSSIBILITIES IN WEATHER MODIFICATION

BY U.S. WEATHER BUREAU

Note	IX
Foreword	XI
Previous conclusions	1
Advisory Committee on Weather Control, conclusions	1
American Meteorological Society, conclusions	2
World Meteorological Organization, conclusions	3
General conclusions	3
Cloud-seeding techniques	4
Cloud seeding from aircraft	5
Seeding from balloons and rockets	5
Seeding from generators on the ground	5
New seeding techniques	6
Reports on recent experiments, related developments and conclusions	7
Recent experiments in the United States	7
Santa Catalina Mountain project	7
Santa Barbara project	8
Project Skyfire	8
Hurricane research	8
National Science Foundation program	8
Foreign experiments	11
United Kingdom	11
Australia	11
Switzerland	11
African Congo Basin	12
British East Africa	12
U.S.S.R.	12
Weather modification and climate control in general	12
Natural controls of weather and climate	13
Large scale tests involve sequence of events	16
Other forms of limited weather modification	18
Changes in outlook	18
Further research	18
Weather Bureau Research	19
General circulation project	19
National hurricane research project	19
Numerical weather prediction	19
Physical research program	19
Meteorological satellite research program	19
Severe storm research	19
Further proposals (a comprehensive plan for studies in weather modification)	19
Future prospects	21
Bibliography	21
Appendixes	25

ILLUSTRATIONS

Figure 1. Areas in which cloud seeding operations have been conducted	2
Figure 2. Cloud build up leading to precipitation	4
Figure 3. Photograph showing artificial nucleation of clouds	6

ILLUSTRATIONS—Continued

Page
Figure 4. Radarscope of hurricane Helene 9
Figure 5. Laboratory apparatus used in investigations of clouds and rain 10
Figure 6. Variation in precipitation between wet and dry years 14
Figure 7. High altitude photograph useful in cloud studies 17

PART 2

WEATHER MODIFICATION AS A NEW TECHNIQUE TO INCREASE WATER SUPPLIES

BY A. M. EBERLE

Foreword 29
Introduction 31
How precipitation is produced naturally 31
Weather modification 31
How does weather modification work 32
The Advisory Committee on Weather Control 32
Conclusion of Committee 35
South Dakota 35
Project Overseed 36
Project Sailplane 36
Project Skyfire 36
Project Seabreeze, 1956 and 1957 36
Santa Barbara project 36
Statement of policy on weather modification, American Meteorological Society 37
What some scientists are saying 38
Batton and Kassander 38
University of Chicago 38
British Meteorological Office 38
F. A. Berry 38
H. G. Houghton 38
Howard T. Orville 39
Joseph Kaplan 39
Roscoe R. Braham, Jr 39
Meteorology Department, University of Chicago 39
Royal Meteorological Society 39
Richard G. Semonen 39
Richard Sänger 40
H. G. H. Ligda 40
Vance E. Moyer 40
American Meteorological Society 40
Irving P. Krick 40
Dallas, Tex., project 40
Oklahoma City project 40
Springfield, Mo., project 40
Shreveport, La., project 40
Paul E. Ruch 40
Wallace E. Howell 41
Ralph D. Kline 41
Economic implications 42
Conclusions and recommendations 43
Recommendations of the Advisory Committee on Weather Control 44
Recommendations by writer 44
Bibliography 45

ILLUSTRATIONS

Chart 1. Effect of artificial nucleation on clouds below natural nucleation level 33
Chart 2. Effect of artificial nucleation on clouds above natural nucleation level 34

NOTE

In his letter of July 13, 1959, the chairman of the Select Committee on National Water Resources, U.S. Senate, requested comments on all aspects of the field of weather modification and a report on means of assuring the most rapid progress in this subject. The request asked also for a description of weather modification techniques with emphasis on recent progress. These subjects are summarized in the paragraphs under their respective headings.

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FOREWORD

Weather modification in its broadest sense includes all manmade changes in natural conditions of weather or climate. It applies to a wide variety of atmospheric phenomena ranging in scale from the micrometeorology of the air overlying a few square feet of land or sea to the vast general circulation of the atmosphere enveloping the entire globe. Man may modify the weather, often in an undesirable way, through many of his normal activities, such as polluting the air with smoke and industrial fumes. On the other hand, he may try to modify the weather in a beneficial way, such as inducing rain to fall from nonprecipitating clouds. This report deals primarily with cloud modification as a means for increasing rainfall (commonly called rainmaking). It touches only briefly on other aspects of weather modification that are related to water resources problems.

Cloud modification by artificial seeding with one or another of several agents has been extensively tested. What conclusions can be drawn from these tests? Perhaps to those not previously acquainted with the facts, the answer may be surprising: the principle conclusion from these tests so far is that much uncertainty still remains in the results of cloud seeding and in the practical utility of present methods for artificially increasing rainfall.

More than $10 million and many years have been devoted to these studies. They have included many thousands of field tests in hundreds of localities, in more than a score of countries, and on every continent. Despite all these intensive efforts, manmade rain is not yet a reliable and proven source of water for localities where an increase in water supply is vital. But this is not lost effort, for it is placing research in weather modification and rainmaking on a scientific basis far ahead of the meager knowledge at hand when modern tests were begun over 12 years ago. Very much more research must be done to bring out the meteorological conditions that determine where, when, how, and under what circumstances man's water resources may be augmented by artificial inducement of precipitation. There are good scientific reasons for believing that undeveloped possibilities in weather modification and rainmaking should emerge from a vigorous research effort to remove the uncertainties.

This report reviews some of the difficulties and uncertainties that have beset practical applications of techniques for increasing natural rainfall, summarizes the few definite conclusions that have been reached, outlines some of the problems that must be solved to bring out possible practical means of weather modification, and briefly describes proposals for research and development in the weather modification approach to augmenting water resources.

WEATHER MODIFICATION

Part 1

PROGRESS AND POSSIBILITIES IN WEATHER MODIFICATION

PREVIOUS CONCLUSIONS

Historical note.—Proposals for modifying the weather and experiments aimed at "making rain" extend back over many decades. In fact, their history covers many centuries if one includes the practices of ancient oracles and other mystics, some of whom had at least vague, though inadequate physical reasons for their methods. Readers who wish to examine methods and experiments prior to 1946 may find the bibliography at the end of this report of interest, particularly the references pertaining to experiments by Dyrenforth in the 1890's (references 1, 2, and 3) who used explosions in the hope of coalescing cloud droplets to form rain, the use of bombs by Post in 1911–12 (reference 2), and especially, the work of Veraart of Holland in 1930 (references 4 to 7). The latter used dry ice alone and in mixture with water-ice, methods which resemble cloud seeding techniques used in recent years. However, much of the physical groundwork for current theories of rainfall formation and cloud modification practices was laid a few years later by the work of Bergeron and Findeisen.

The modern phase of experimentation in use of nucleating and coalescing particles to induce precipitation of rain or snow was opened by Langmuir and Schaefer in their cloud seeding experiments with "dry ice" (solid carbon dioxide) near Schenectady, N.Y., in 1946. These experiments have been described in many published articles, among them references 8 and 9. Discovery of the spectacular visual effects of cloud seeding with solid carbon dioxide and, later, silver iodide and certain other particles led to explosive growth of interest and experimentation in rainmaking not only in the United States but also in many countries abroad. During the 10 years 1947–57 there were many thousands of field tests, some under fairly adequate scientific management and many more in commercial applications or in feverish efforts to relieve drought-stricken localities. Figure 1 shows approximately the areas covered by cloud-seeding operations at various times since 1947. During this period the many rumors and unverified claims of great success in rainmaking led to much waste of effort, time, and money, and, even more serious, diverted attention and support from the fundamental research that has now been recognized as prerequisite to sound and realistic development of the possibilities of rainmaking and other forms of weather modification and climate control, possibilities that are little understood and still undetermined.

ACWC conclusions. The best scientific studies and experimentation in seeding natural clouds have been thoroughly reviewed by different technical groups and published in well-documented scientific papers. In order to summarize the results of cloud seeding to increase precipitation as the subject stood at the close of 1957, the following conclusions are quoted from the final report of the Advisory Committee on Weather Control (ACWC), a body appointed by the President. See reference 10 for the full report.

On the basis of its statistical evaluation of wintertime cloud seeding using silver iodide as the seeding agent, the committee concluded that—

(1) The statistical procedures employed indicated that the seeding of winter-type storm clouds in mountainous areas in western United States produced an average increase in precipitation of 10 to 15 percent from seeded storms with heavy odds that this increase was not the result of natural variations in the amount of rainfall.

(2) In nonmountainous areas, the same statistical procedures did not detect any increase in precipitation that could be attributed to cloud seeding. This does not mean that effects may not have been produced. The greater variability of rainfall patterns in nonmountainous areas made the techniques less sensitive for picking up small

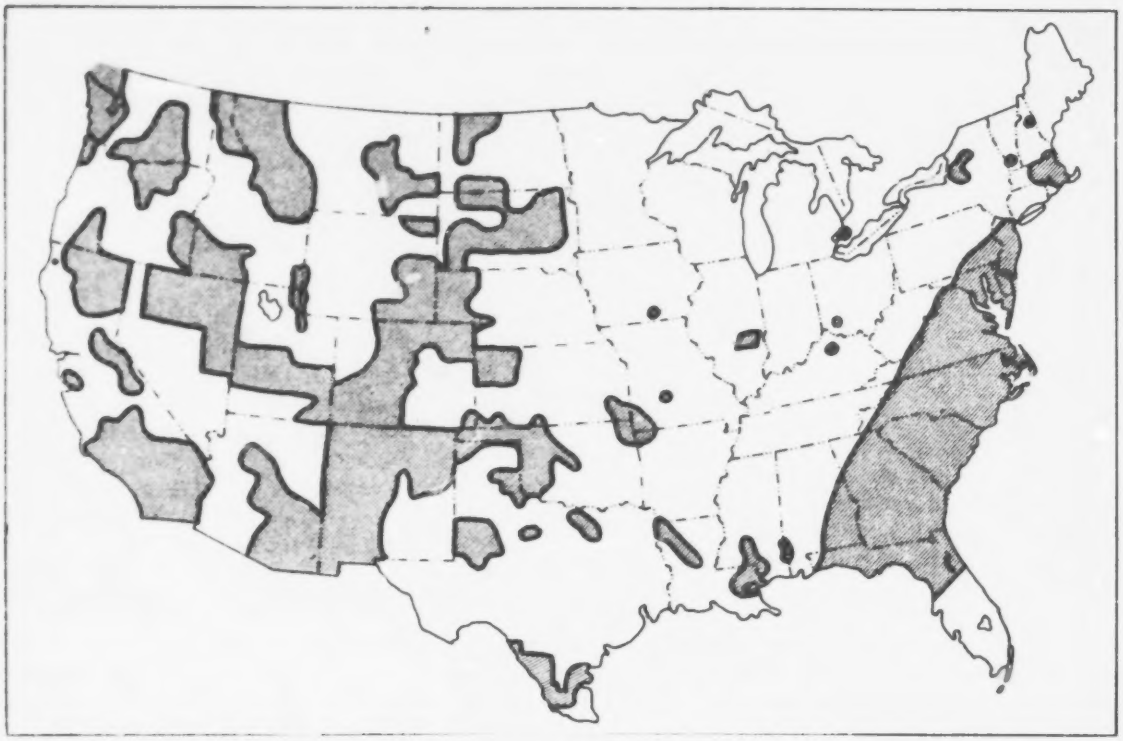

FIGURE 1.—Approximate areas of the United States where cloud-seeding operations have been conducted in recent years.

changes which might have occurred there than when applied to the mountainous regions.

(3) No evidence was found in the evaluation of any project which was intended to increase precipitation that cloud seeding had produced a detectable negative effect on precipitation.

(4) Available hail frequency data were completely inadequate for evaluation purposes, and no conclusions as to the effectiveness of hail suppression projects could be reached.

AMS conclusions.—Because of the potential importance of the subject and the doubts incident to the many unverified and sometimes controversial reports in the daily press and over radio and television, the American Meterological Society (AMS) in 1957 published conclusions that the society had reached more or less independently (reference 11). These agreeing in substance with the conclusions by ACWC quoted above were as follows:

1. The seeding of supercooled cloud with dry ice will usually convert at least a portion of the cloud to ice crystals. Under appropriate conditions such seeding may release variable amounts of precipitation from fairly deep and active cumulus clouds in which the natural release of precipitation has not already started. Small, inactive cumulus clouds are usually dissipated when they are seeded with dry ice. Holes or valleys may be produced in supercooled layer clouds or supercooled fogs by seeding them with dry ice.

2. The injection of water drops or hygroscopic salt particles into active, warm (nonsupercooled) cumulus clouds may release some rain. Small, inactive, warm cumulus may often be partially or completely dissipated by seeding them from above with water drops or other particles; such dissipation may occasionally be accompanied by the release of very light rain.

3. In some cases warm fog and stratus may be dissipated in restricted regions by the use of certain hygroscopic materials.

4. At temperatures below about −5° C. silver iodide crystals are known to affect supercooled clouds in much the same way as dry ice. The frequent absence of clear-cut results following the operation of ground-based silver iodide generators is believed to be due to one or more of the following causes: (*a*) The failure of the seeding material to reach the supercooled clouds; (*b*) the absence of clouds that could be affected by seeding; (*c*) the decay of the silver iodide; (*d*) the presence of an ample supply of natural ice crystals; (*e*) topographical influences which defy quantitative measurement.

5. Cloud seeding acts only to trigger the release of precipitation from existing clouds. The release of sub-

stantial amounts of precipitation by either natural or artificial means requires the preexistence of an extensive moisture supply in the form of moist air currents and of active cloud-forming processes. For this reason the meteorological conditions most favorable for the artificial release of precipitation are very much the same as those which usually lead to the natural release of precipitation. This factor plus the extreme natural variability of precipitation makes the evaluation of the effects of seeding difficult and often inconclusive.

6. Evaluations performed by independent agencies have yielded reasonably convincing evidence of increases of precipitation due to the operation of ground-based silver iodide generators only for operations conducted in cold weather in regions where forced lifting of the air over a mountain range is an important factor. No convincing evidence has been presented which indicates that ground-based silver iodide seeding affects the amount or character of the precipitation over flat country. This does not prove that there are no such effects but suggests that, if present, they are too small to be detected by statistical analyses of data available to this date.

7. In the absence of a truly quantitative theory of precipitation the best present means for obtaining a quantitative estimate of the effect of seeding on precipitation is through the statistical evaluation of randomized cloud seeding experiments. The randomization is necessary to insure valid interpretation of the results, and a long series of such experiments may be necessary to detect small effects.

8. Present knowledge of atmospheric processes offers no real basis for the belief that the weather or climate of a large portion of the country can be significantly modified by cloud seeding. It is not intended to rule out the possibility of large-scale modifications of the weather at some future time, but it is believed that, if possible at all, this will require methods that alter the large-scale atmospheric circulations, possibly through changes in the radiation balance.

9. All cloud seeding operations should be considered as experiments since the techniques are still under development and there is no sound basis for the quantitative estimation of the results in advance of the operation. As experiments they should be designed primarily to yield optimum scientific results. There is good reason to believe that improved returns from cloud seeding will result from a sound experimental approach and this should be fostered by all concerned.

WMO conclusions.—The World Meteorological Organization (WMO), specialized agency of the United Nations in the services of weather science and its applications, appointed independently a group of international experts who summarized the status of rainmaking in WMO Technical Note No. 13, "Artificial Control of Clouds and Hydrometeors" (reference 12) (hydrometeors—rain, snow, hail, and other forms of precipitation). Principal conclusions were:

1. On a number of occasions seeding from aircraft has beyond reasonable doubt led to a modification of clouds and a release of precipitation by processes for which there is a satisfactory qualitative but not yet a quantitative theory.

2. At present, in the absence of a quantitative theory and certain climatological data, it is not possible to predict the result of protracted seeding operations in any particular place, especially if they are carried out from the ground. Nevertheless, there is some justification for supposing that where certain special kinds of cloud frequently occur, skillfully conducted seeding operations might result in a local net increase in precipitation of economic benefit. At present this supposition can be justified only in respect of simple supercooled orographic clouds, and cannot yet be extended to include places where other, more complex cloud systems are predominant and provide most of the natural precipitation.

3. In our opinion, a net increase of precipitation has not been demonstrated beyond reasonable doubt in any seeding operations yet described in the scientific literature, and it seems that at least most of the claims made in other publications and in newspapers have not had adequate foundation.

4. At least several years of fundamental investigations and of meticulously planned and analyzed seeding experiments will be needed before a reliable assessment of the economic potential of seeding operations can be made.

General conclusions.—Study of the carefully worded conclusions given in reports by the several independent national and international bodies shows that at the close of 1957, the direct evidence of success in inducing rain to fall in large quantity by artificial means was disappointingly small, despite a decade of experimentation, thousands of field tests in many different localities in the United States and abroad and many unverified claims of success published in the daily press and in various periodicals. However, there were promising indications of moderate success in increasing rainfall in areas where orographic conditions and moist upslope winds gave a more or less continuous source for formation of subcooled clouds. Even in these cases the results lacked positive proof, the uncertainties being due to difficulties of conducting tests with adequate experimental controls. Conclusions up to this time did not imply failure; they simply demonstrated what had been foreseen many years earlier, that is, much research into the fundamentals of cloud physics and formation of rain and field tests must be conducted under conditions of good scientific design and experimental controls before definite conclusions can be reached as to whether rain and snow can be induced artificially in sufficient quantity to be of much value economically.

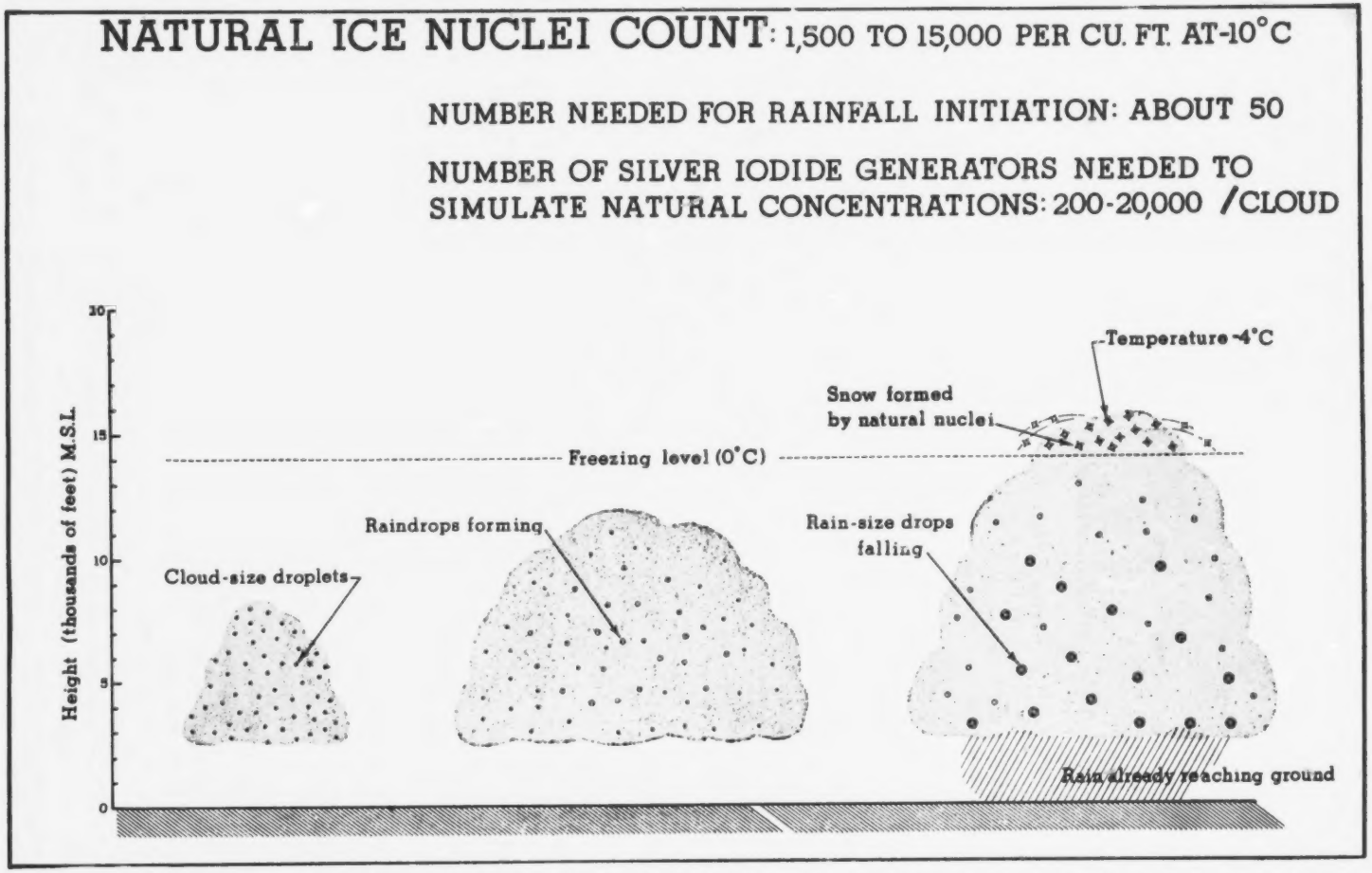

FIGURE 2.—Clouds building up beyond the freezing level remain in the liquid stage unless freezing nuclei are present. The ice stage, a development frequently but not invariably associated with the precipitation process, may be initiated by natural nuclei or by the introduction of seeding agents into the supercooled portion of the cloud.

The conclusions of the Weather Bureau during 1950 and 1951 were essentially the same as expressed on the preceding page and, based on these conclusions, the Bureau strongly urged an expanded program of basic research.

CLOUD-SEEDING TECHNIQUES

Under this subject as in other portions of this report the discussion applies mostly to techniques for increasing the quantity of rainfall. Plans and methods under study or now in use in other forms of weather modification are mentioned briefly in the section on "Weather Modification and Climate Control in General." The use of solid carbon dioxide and silver iodide to introduce "sublimation" or condensation nuclei into clouds is obviously applicable only if the cloud droplets are at temperatures below freezing. The conditions illustrated in figure 2 are commonly observed in the atmosphere particularly during the warmer seasons and imply some of the limitations in seeding by dry ice or silver iodide. Several different techniques have been used in cloud seeding. Without repeating the details published in the articles referenced in 8 and 9 and in 13 through 20, the principal methods for inducing rainfall are summarized in succeeding paragraphs.

Cloud seeding from aircraft.—One of the obstacles to seeding effectively is the difficulty of injecting the seeding particles into the particular portions of the cloud where they are expected to cause droplet freezing, accretion or coalescence. When seeding particles are sent into the cloud by balloon or rocket, or are discharged from generators installed on the ground in the expectation that the winds and convectional air currents will waft the particles to those parts of the cloud where they will be effective, it is practically impossible to make certain whether or not they actually reach those parts of the cloud unless aircraft are employed to take samples of the air at cloud heights and trace the paths of the particles. In fact, it is quite certain in many cloud-seeding operations in which ground generators have been used that the seeding particles never reached the clouds and whatever changes were observed in the cloud were the result of natural causes and not due to artificial seeding. The best method so far developed for placing cloud-seeding particles where they will be most effective is the use of dispensers or generators carried in aircraft and flown where the particles may be discharged into the cloud or just above the cloud. The hundreds of seeding operations using aircraft to discharge the seeding materials have shown conclusively that this method is an important feature in sound evaluation of the results of seeding. The seeding materials commonly used in this method are solid carbon dioxide, silver iodide, or water spray with or without salt in solution. Recently carbon black has also been used in seeding. Cupric sulfide has been considered for use by some experimenters; also special substances such as red phosphorus (in Russia) and aluminum oxide (in Japan), but these substances have not been used to any great extent. The results and conclusions are summarized in the findings given in the several paragraphs under the headings "Previous Conclusions" and "Reports of More Recent Experiments, Related Developments and Conclusions."

Seeding by balloons and rockets.—While used in relatively few localities, there have been numerous tests of rockets and balloons as vehicles to carry seeding materials into selected portions of clouds. In British East Africa and Italy especially, these vehicles have been used for routine cloud-seeding operations. Although not as certain as use of aircraft, a well-designed rocket permits rather good control of the point where seeding material is discharged within the cloud. Balloons can be used to discharge the seeding materials within the cloud provided the estimate of path from the point of release of the balloons from the ground is reasonably accurate, but control of seeding is not as positive as in the use of aircraft or rockets. Tests of these methods have not yet been fully evaluated.

Seeding from generators on the ground.—By far the greatest number of cloud-seeding attempts have been made with use of silver iodide generators operated on the ground. Certain other seeding chemicals can be discharged through ground generators but silver iodide is the most commonly used. Sodium chloride (common salt) has been used in some experiments but not under circumstances that would permit realistic evaluation of the results and possibilities. Obviously the rapid evaporatation of solid carbon dioxide in open air precludes its use as a seeding agent to be dispensed from ground generators except under such unusual circumstances as installation on a mountaintop

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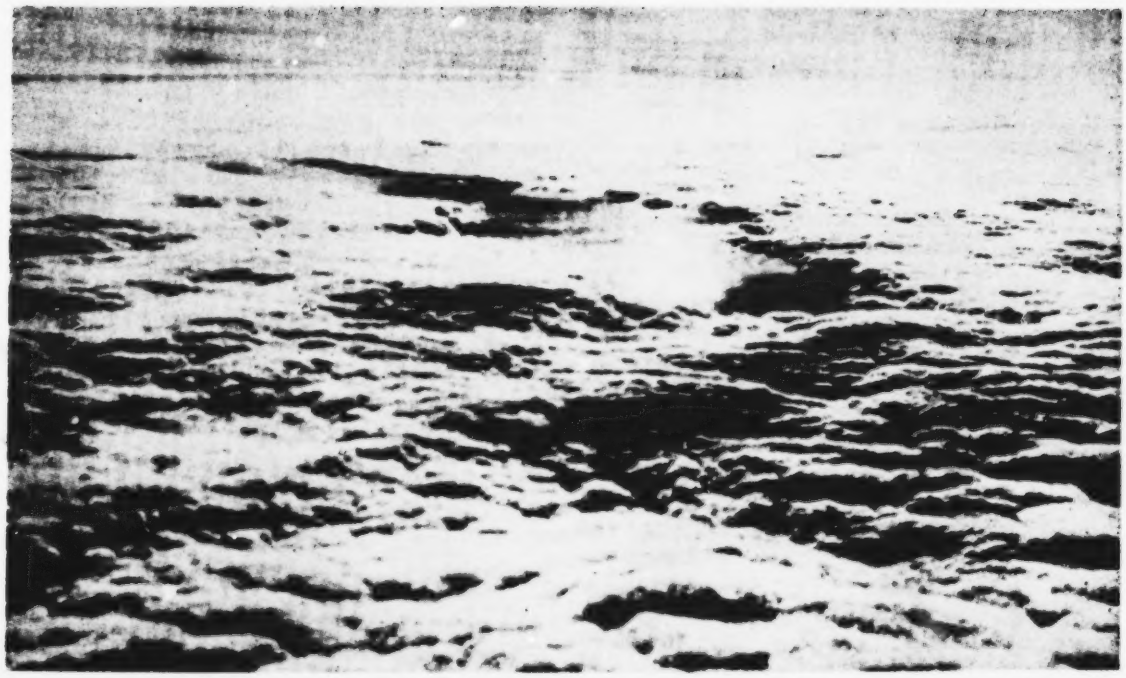

FIGURE 3.—The first photograph showing artificial nucleation of a portion of a supercooled cloud, April 7, 1947. The width of the channel left by the cloud-seeding plane at its widest point is 1⅞₁₀ miles. The small illuminated portion, where light is reflected from a crystallized area, is evidence that ice crystals are being formed from supercooled cloud droplets. The cloud bank is at 14,000 feet, and the altitude of the plane making the photograph is 16,000 feet. (U.S. Army photograph, Project "Cirrus.")

within the clouds. The literature contains descriptions of seeding dispensers and generators, and recommendations on preparations of seeding materials, rates of seeding and other operating instructions, but these particulars are beyond the intended scope of this report. Detailed descriptions of design and operation of dispensers and generators are given in references 16, 17, and 18. The well-known photograph of cloud seeding by Langmuir and Schaefer in 1947 shows the spectacular visible results of this method. This photograph is reproduced in figure 3. These effects led immediately to expectations of much greater results in "rainmaking" than turned out to be the case.

Cloud-seeding operations with ground generators have too frequently been under conditions which do not permit evaluation. Among the uncertainties that prevent reasonable evaluation of whether the seeding succeeds in increasing the quantity of rain or snow have been (1) the ceaseless changes in clouds, winds, vertical currents, moisture, and precipitation under which such operations normally have to be conducted (these changes always make it possible and, in many cases, probable that any and all rainfall in the individual case is due to natural causes rather than to artificial seeding); (2) dependence on air currents and turbulence to carry the seeding material into the cloud and distribute it effectively (it is known that in many cases the material is not carried into the clouds where it might be effective); (3) poor quality control over output of generator (in some cases in which seeding was thought to have been successful it has subsequently been found that the generator was inoperative); and (4) lack of scientific design characteristics, and other experimental controls essential to practical evaluation.

New seeding techniques. While there have been variations in the kinds of equipment and methods used they have all been based essentially on the techniques mentioned in the preceding paragraphs. There have been no revolutionary im-

provements in methods or equipment, and so far as is known, no proposals up to October 1959 for changes in the basic principles to be used.

REPORTS ON RECENT EXPERIMENTS, RELATED DEVELOPMENTS, AND CONCLUSIONS

This section refers to recent research and experiments, most of which are currently in progress. While the research projects and field testing in cloud seeding here and abroad are much too numerous to describe in detail in this report, a few of the most noteworthy can be reviewed briefly. They are indicative of the nature of all research in artificial inducement of precipitation. The conclusions to be drawn from the most noteworthy are representative of findings up to the present time with respect to all rainmaking experiments everywhere, as far as known in the United States.

Recent experiments in the United States.—Theoretically the most favorable conditions for artificially increasing the quantity of precipitation should be found in regions and localities where warm moist winds blow more or less constantly up the slopes of high mountains. If their tops reach well above the usual height of condensation of water vapor, clouds are caused to form in abundance on the windward slopes. These conditions give a continuing source of cloud droplets to replenish those which are precipitated as rain or snow or are evaporated as the wind carries them downward on the leeward slopes. Condensation of the invisible water vapor in the air into cloud droplets through gradual ascent as the wind is forced upward along the mountain slope resembles the warm front system found in nature whereby the ascending air, cooled by expansion, gives up its moisture through condensation first into myriads of cloud droplets and eventually as rain or snow if the process proceeds sufficiently far and a mechanism is present for droplet accretion or coalescence. Warm front systems formed by the surface between air masses are the way in which nature brings the steady and prolonged light rains that restore the water supply in some parts of the temperate and polar zones. When the cloud droplets are at temperatures below freezing, optimally colder than −10° C. (14° F.) for silver iodide and −5° C. (23° F.) for solid carbon dioxide, these seeding materials may be used to induce or increase precipitation. Evidence from many experiments with these methods indicates that they have not yielded as much induced precipitation as theory would suggest. Further research is needed to find the discrepancy.

Santa Catalina Mountain project.—Important research in cloud seeding in a mountainous region is in progress over the Santa Catalina Mountains near Tucson, Ariz., by the Institute of Atmospheric Physics of the University of Arizona. The project makes use of aircraft to dispense silver iodide into the clouds at selected levels upwind from the mountain range. Seeding operations are carefully randomized and documented, being accurately timed and recorded by cloud photographs and radar observations which indicate the beginning and development of precipitation. Rainfall is accurately measured by a network of raingages insofar as possible. These control records give a basis for analyzing cause and effect during the seeding process. Preliminary conclusions from data taken during two summers have been reported as follows (reference 21):

> When data from both years were combined it was found that the mean rainfall per gage was 30 percent higher on the seeded days; however, the probability that the observed differences in the mean rainfall occurred by chance was quite high, about 0.14. This value was obtained from a sign-rank test which made use of a ranking of the differences of the mean rainfall of pairs of days. A comparison of the extreme rainfalls on seeded and nonseeded days showed greater differences, but the statistical confidence of a real difference was still not sufficiently high to be acceptable.
>
> However, in 1958, it was found that on the seeded days there were about 9 times more lightning strokes than on the not-seeded days.
>
> Although the results to date point toward the conclusion that seeding produced important effects, it is vital that more data be compiled in order to be sure that the results have not been brought about by chance.

Other significant conclusions from this project are given in the reference, but further observations are needed to determine what the findings mean in terms of practical applications. These studies are continuing.

An important feature of the project is the attention given to some of the fundamental and quantitative factors involved in effective seeding of clouds and in evaluating the results. These are important steps toward better understanding of the physics of cloud formation and precipitation. They are illustrative of other projects,

some in the laboratory, others in the open air, needed to isolate and analyze the various factors involved in the complex process of rain formation. See reference 22.

Santa Barbara project.—Several cooperating agencies organized this study in 1956–57 to measure the increase in rainfall for water-supply purposes on the slopes of mountains north and northeast of Santa Barbara, Calif. The project employs silver iodide dispensed from ground generators as the seeding material. Preliminary surveys of windflow and eddy motion led the research leaders to believe that wind and turbulence would carry enough of the seeding material into the clouds to be effective, although in any individual case of seeding this is not a certainty since no practicable tracer system is available. Informal reports of this project during the first year of operation were encouraging, but later discussions opened up questions regarding the suitability of the statistical analysis. Present information indicates that seeding during 1958 and 1959 did not give definite results Final conclusions have not yet been announced. A recent statement is that the project will be continued.

Project Skyfire.—The U.S. Forest Service with cooperation of others has conducted cloud-seeding operations near Missoula, Mont., primarily for the purpose of determining whether cloud seeding could be used to reduce the number of lightning strikes that cause forest fires. This work is based on the possibility of overseeding the cumulus clouds before they can reach the cumulonimbus stage and also the possibility of altering the electrical structure within the thunderstorm clouds. The theory underlying this method is not necessarily contradictory to the effects obtained at Tucson where lightning was observed more frequently after seeding. The differing results may depend on the amount of seeding, the stage of development of the cumulus or cumulonimbus when seeded, on the method and place (in the cloud) of seeding, and on other factors still unknown. Because of the scattered distribution of clouds to be seeded in the northern Rockies, the rough terrain which makes it difficult to install radar, raingage networks, and other technical controls for the experiment, the results have not yet been conclusive. Impressions of observers are that seeding has been effective in some cases. Further tests with technical controls are necessary to give data that can be objectively evaluated.

Hurricane research.—Beginning in the summer of 1956, comprehensive observations of hurricane structure have been undertaken with specially instrumented aircraft flown into these severe storms. One phase of this research has included measurements of the hurricane's cloud characteristics and possibilities of using seeding material (reference 23). Tests have been conducted. Although there were no obvious results, these experiments will be continued under appropriate conditions. Figure 4 shows a typical pattern of hurricane rainfall as observed by radar, a vital tool in assessing the results of any such experiments.

Many other research projects in cloud physics relating more or less directly to the problems of cloud seeding are in progress in Government and university laboratories. These have for their primary goals a more exact understanding of condensation and freezing processes, the manner in which raindrops and snow crystals develop and grow, the kinds and number of particles which act as natural nuclei, and many other unsettled questions. Special facilities such as those shown in figure 5 have been developed for some of these investigations. A comprehensive listing of research projects has been undertaken by the National Science Foundation under the terms of its basic statutes and it is expected that this list will be available for Government bodies in the near future.

NSF program.—In 1958 Congress enacted Public Law 85–510 directing the National Science Foundation (NSF) "to initiate and support a program of study, research, and evaluation in the field of weather modification * * *." In October 1958 the Director of the Foundation appointed an Advisory Group on Weather Modification composed of leading scientists in the field of cloud physics, associated with universities and private research institutions. He also appointed an Interdepartmental Committee on Weather Modification to bring together representatives of the several departments of Government engaged in or interested in development of various forms of weather control.

During 1959 the Foundation sponsored three conferences or workshops of scientists, statisti-

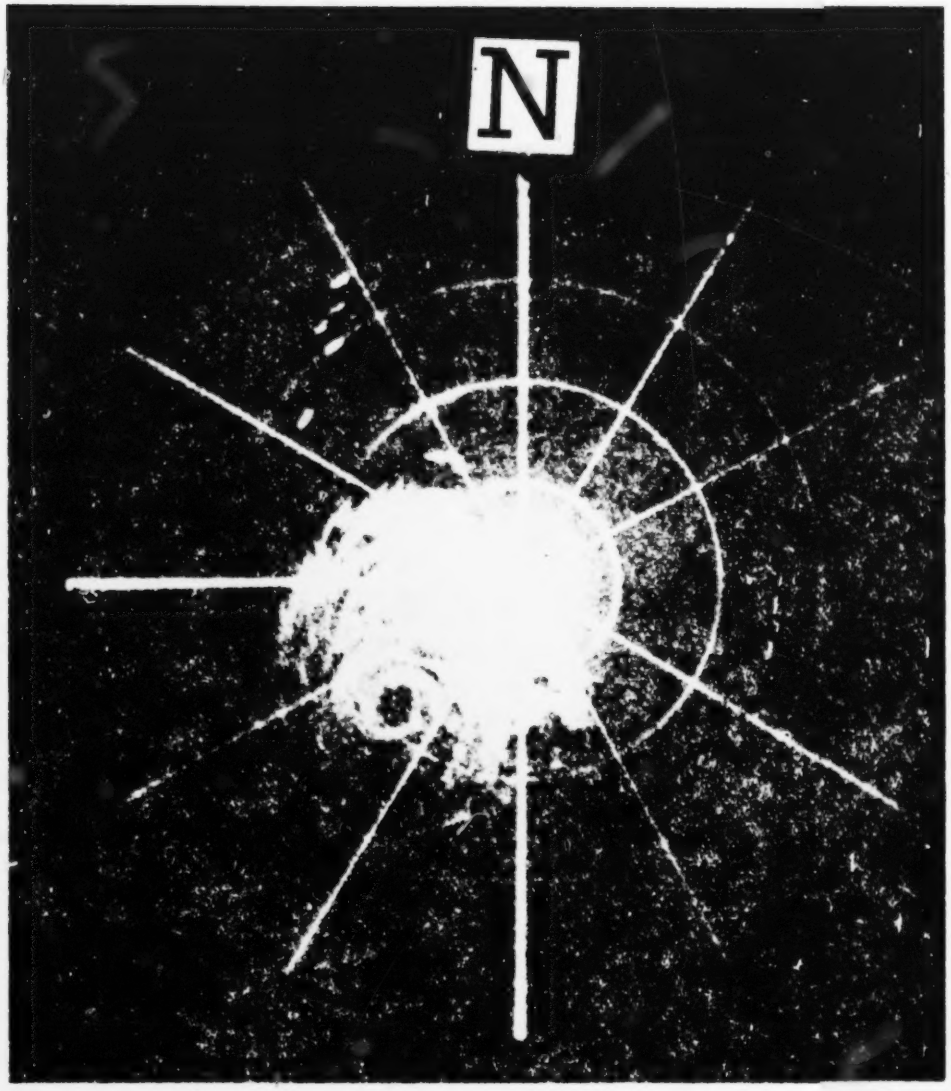

Figure 1.—Radar scope of Hurricane Helene, showing spiral rainbands and the eye of the hurricane located 90 nautical miles west of radar station at Cape Hatteras, N.C., September 27, 1958. Exploratory flights of the effect of seeding on hurricane clouds have been conducted by the National Hurricane Research Project. The concentric circles are spaced at 50-mile intervals. They show the huge extent of a hurricane.

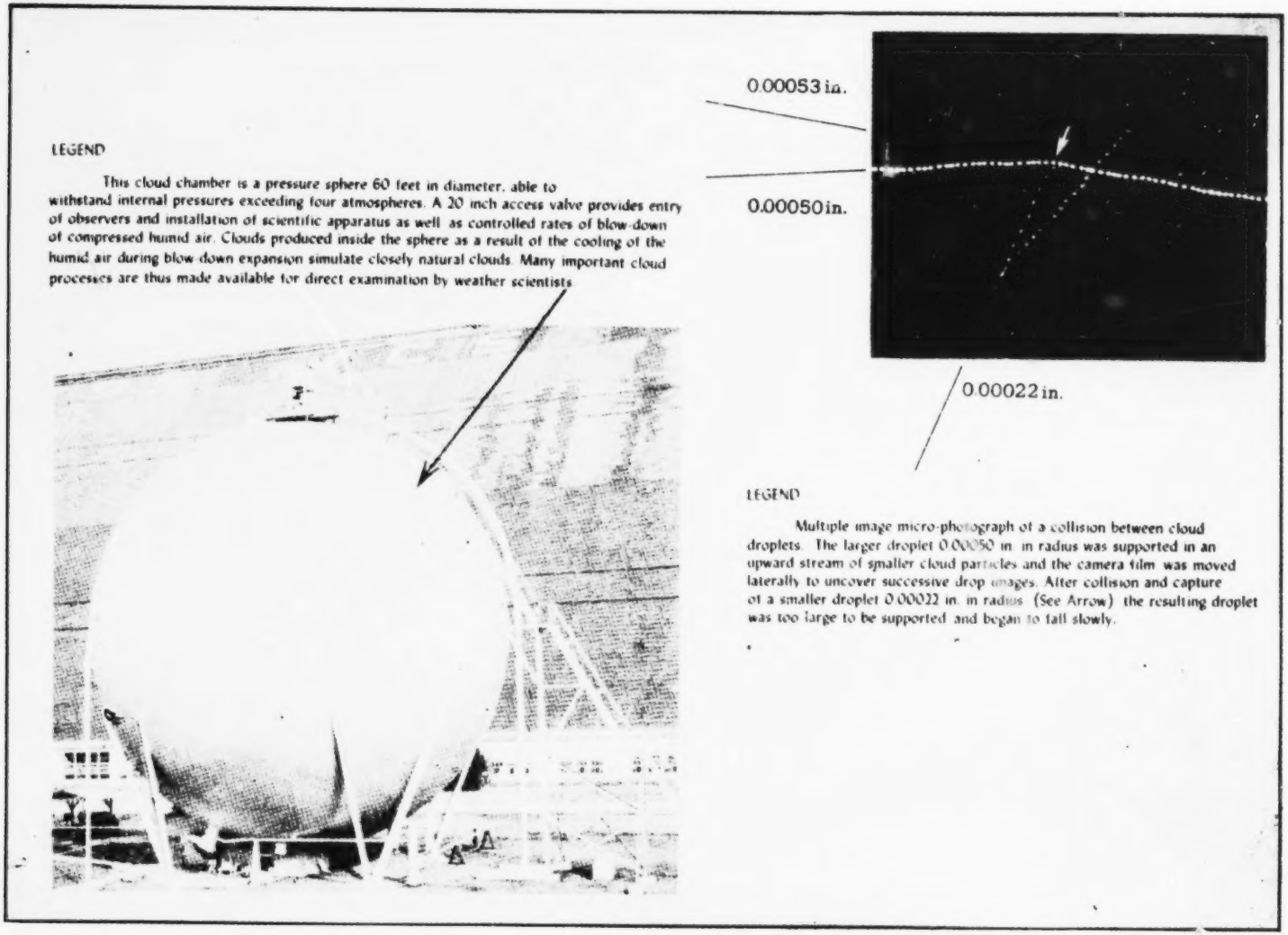
LEGEND
This cloud chamber is a pressure sphere 60 feet in diameter, able to withstand internal pressures exceeding four atmospheres. A 20 inch access valve provides entry of observers and installation of scientific apparatus as well as controlled rates of blow-down of compressed humid air. Clouds produced inside the sphere as a result of the cooling of the humid air during blow down expansion simulate closely natural clouds. Many important cloud processes are thus made available for direct examination by weather scientists.
0.00053 in.
0.00050 in.
0.00022 in.
LEGEND
Multiple image micro-photograph of a collision between cloud droplets. The larger droplet 0.00050 in. in radius was supported in an upward stream of smaller cloud particles and the camera film was moved laterally to uncover successive drop images. After collision and capture of a smaller droplet 0.00022 in. in radius (See Arrow) the resulting droplet was too large to be supported and began to fall slowly.

FIGURE 5.—An example of laboratory apparatus and techniques used by the Weather Bureau in investigations of the formation of clouds and rain.

cians, and engineers active in cloud physics and related subjects of importance in development of effective methods of cloud seeding. One of these conferences held in Cambridge, Mass., in February 1959 discussed problems of instruments and measurements for cloud-seeding experiments. The second conference concerned design and evaluation of field tests. It brought together the leaders in these aspects of cloud seeding at a meeting at Big Meadows, Va., in May 1959. The third was held at the Woods Hole Oceanographic Institution in June 1959 to study the scientific basis for weather modification in theory and in practice with particular emphasis on the mechanisms of precipitation formation. Participants included physicists, chemists, and meteorologists in order that the several scientific disciplines involved in weather modification might be well represented. These activities together with the many research projects supported by the Foundation and other interested departments of Government show the vigorous attack now being made on the scientific fundamentals that are indispensable to discovery of the possibilities of weather modification and the design of effective methods for its application.

Foreign experiments.—As in the case of U.S. efforts in weather modification, many experiments have been undertaken in other countries. There is considerable emphasis on cloud physics and laboratory studies in Great Britain, Australia, Japan, and the U.S.S.R. Reference 24 contains a comprehensive review of the research programs in the latter country based on information available to Western scientists. Reference 25 is a recently published review of the subject prepared by a committee of the World Meteorological Organization composed of internationally recognized experts in the field which, however, does not modify the conclusions by this organization as quoted on an earlier page of this report. Several of the more noteworthy investigations are mentioned briefly here.

United Kingdom.—An analysis of the interim results following 3 years of seeding trials with silver iodide generators (reference 26) in the Salisbury Plain area of the British Isles indicated that the rainfall in the target area has been less by an average amount of about 15 percent than that occurring in the surrounding areas used for comparison. The statistical procedures used resulted in this estimate being judged as "significant." Corollary physical experiments using tracer materials for studying the diffusion of particles released from the ground raised doubts that seeding agents reached appreciable heights, and the report states:

> The one conclusion of which we can be reasonably sure, since both statistical and physical arguments lead to it, is that we have not produced any appreciable *increase* of rainfall. It does not of course follow that all cloud seeding is useless; it is even conceivable that the same procedure, applied in other meteorological conditions, might be effective. But it seems almost certain that seeding on this scale (which is about the same as that employed in commercial rainmaking) is ineffective when used on frontal cloud in level country. This conclusion is in agreement with the findings of the U.S. Advisory Committee on Weather Control which states: "In non-mountainous areas * * * statistical procedures did not detect any increase in precipitation which could be attributed to cloud seeding." The same report adds, however: "No evidence was found in the evaluation of any project which was intended to increase precipitation that cloud seeding had produced a detectable negative effect on precipitation."
>
> It seems therefore that, if the decrease we appear to have produced is real, it is a unique result.

Australia.—A series of randomized airborne cloud-seeding tests with silver iodide have been pursued vigorously over a 5-year period making use of orographic conditions in the Snowy Mountains area. Preliminary data have been reported as indicating favorable but not conclusive results (reference 27) with possible increases of about 15 to 20 percent within the hydrological catchment area. The continuity of these experiments over a period of several years has been an advantage which has led to the hope that they will contribute important information on rainmaking for purposes of water storage and irrigation.

Switzerland.—A current series of randomized ground seeding experiments with silver iodide began in 1957 for the purpose of evaluating the prospects of hail suppression under summer orographic conditions. Appreciable differences in rainfall between seeded and nonseeded periods were observed the first year, but comparable differences were discovered outside the target area and in a region well removed from possible influence by the silver iodide (reference 28). This raised reasonable doubts as to the causes of the

observed differences in the target area itself. Final results are not expected to become available for several years.

African Congo Basin.—Preliminary experiments have been reported using artificial heat sources so far limited to the burning of large areas of vegetation (reference 29). Cloud development apparently was stimulated, but only light amounts of rain occurred. Use of forced convection to stimulate formation of clouds and rain requires a special combination of light winds and very warm, humid air masses of the kind most likely to occur in tropical areas near the Equator. Although the conditions for these experiments were initially judged favorable for seeding, results with these techniques were reported to be disappointing, and these methods were abandoned.

British East Africa.—Experiments of comparatively short duration have been conducted with several techniques including ground-based silver iodide generators and fused charges of gunpowder mixed with seeding agents carried aloft by balloons and rockets. The results have been reported as inconclusive, but the indications were that silver iodide was ineffective under tropical cloud conditions, and use of hygroscopic materials such as sodium chloride may be more promising when dispersed from rockets (reference 14).

U.S.S.R.—Although conducted in 1956 as a hail suppression experiment, the report on this particular limited series of tests in Soviet Russia was only recently published (reference 30). Thirteen seeding trials were made using silver iodide and red phosphorus dispensed from mountain tops, and the experiments included use of radar and trajectory studies with balloons. The observations reported over the target area were highly variable. The radar echoes showed a tendency for precipitation areas to form at lower elevations in the cumulus clouds on seeding occasions. No rainfall measurements at the ground were reported, and reservations were expressed regarding the reliability of ground generators as a means for introducing seeding agents into clouds. The report indicates that much higher quantities of seeding agents were used than are typical of U.S. experiments. Other experiments in cloud seeding in the U.S.S.R. have not been fully reported. Recent communications give some reason to believe that conclusions there have been similar to those quoted in earlier pages of this report. The review contained in reference 24 gives further information on research in the U.S.S.R. Experimentation there appears not to have been as extensive as in Australia, Canada, Italy, Switzerland, United Kingdom, and United States taken together.

NOTE.—With reference to the question occasionally raised in public discussion, as to whether foreign powers are on the threshold of discovery of methods for changing climate on a large scale, possibly for use as a weapon to bring flooding rains and destruction or drought and starvation to countries toward which they are hostile, there is no evidence to support the idea that such discovery is imminent. While part of the research now in progress may be secret, any tests of large scale control of weather or climate would hardly escape detection in a network of weather observations reported four times daily from stations all over the globe. No indications of success in artificial weather control on a great scale have been found in these thousands of weather reports received every day. Falsified reports or secular changes would show up as anomalies in the data and the synoptic patterns. Moreover, through the World Meteorological Organization and other scientific organizations, there are frequent international meetings and exchanges of scientific views. Through these contacts it is known that scientists in other countries are on the whole less optimistic about large scale weather control and public expectations are less speculative than in this country. The reasons for questioning the imminence of revolutionary developments in weather control as a weapon of war are to be found in the remarks under "Weather Modification and Climate Control in General." In addition to the brief reviews of rainmaking research in other countries given in preceding paragraphs the references listed at the end of this report contain much more complete descriptions.

WEATHER MODIFICATION AND CLIMATE CONTROL IN GENERAL

Research in atmospheric sciences has looked into weather modification on the global scale and also sections thereof comprising relatively large geographical areas as well as for the very local scale represented by seeding of individual clouds with intention of increasing rainfall over a certain county or farm. Because of the cost and many

facilities that would be involved in a field test of very large scale weather modification and also because of uncertainty as to the consequence, since man's knowledge of natural controls of weather and climate is now so incomplete, studies of global, hemispheral or continentwide modification of weather and climate have so far been of a theoretical or academic nature rather than experimental. If man knew what causes the vast changes in total rainfall, average temperature, etc., from year to year, not only locally but also in the overall patterns for a continent, and if he knew what caused the periods of extensive glaciation during the ice ages of the past, the knowledge should make it rather easy to calculate the theoretical possibilities and the economic practicabilities of modifying weather and climate on a large scale. One could then also estimate the consequences, desirable and undesirable. An illustration of the large annual variations in rainfall over the United States is given in figure 6 which shows the precipitation patterns for 1956 and 1957 expressed as percents of the normal amounts. During 1956, the year that climaxed a 5-year drought in the Southwestern States, the amounts were less than 50 percent of the average total precipitation for large parts of the Southwest. In marked contrast, during 1957 the total amounts of rain and snow were greater than normal, in some localities more than twice the normal amounts. This was the first year of a period of rainfall somewhat heavier than normal in most parts of the region, a surplus that continues on the whole up to the present time. Variations from periods of wetter than usual to periods of drier than usual have probably occurred for many centuries, perhaps from the beginning, although not with sufficient regularity to be predictable insofar as present knowledge goes.

Lacking knowledge of the causes of these gross changes, it is obvious that plans to control climate on a large scale are little more than speculation. A few of the more noteworthy suggestions and estimates of results are summarized in the next few paragraphs and references given in the list at the end of the report.

Following the great increase in experimentation in cloud seeding after 1946 and the spread of public interest in general there were many studies into the possibilities of producing large scale changes in weather and climate by use of relatively small amounts of silver iodide. A few investigators believed they had discovered effects extending hundreds of miles from the place where silver iodide nuclei were generated and discharged into the atmosphere, and in a few cases experimenters hastily concluded that nuclei emitted in one locality had seeded clouds and caused rain over vast areas halfway across the continent. It was also speculated that periodic operation of seeding generators had produced cycles in atmospheric pressure and in the occurrence of rain, and that a small force applied to the atmosphere at the right point might trigger much larger weather events at great distances. Some of these speculations pertained to phenomena that are little understood at present and are impossible to analyze and explain from data that can be collected now. However, sober scientific review of the cases where seeding was thought to have caused large scale effects over great distances, and careful statistical evaluation of the evidence have given no reasons in support of the speculation. Too little is known at present to justify final conclusions as to the geographical range of effects of cloud seeding or as to where and how frequently there may be conditions of the atmosphere so delicately balanced as to permit small causes to set in motion great effects. (See reference 31.)

Natural controls of weather and climate.—Even the longest accurate records of temperature and rainfall extend back only a century or two. For most localities the records go back less than a century. Compared with the long-period swings in climate between warm and moist at the one extreme to cold and dry at the other, with each swing apparently extending irregularly over several centuries, the length of accurate meteorological records is much too short to provide a satisfactory basis for analysis of the long-term periodicities in climate if they may rightly be called periodic. For studies of the still longer fluctuations represented by the ice ages standard meteorological records are of course practically without significance at present. They are too short by far.

Studied estimates of the climates of the earth during past millenia suggest that the average temperature of the surface of the earth as a whole is only about 15° F., warmer than it was during

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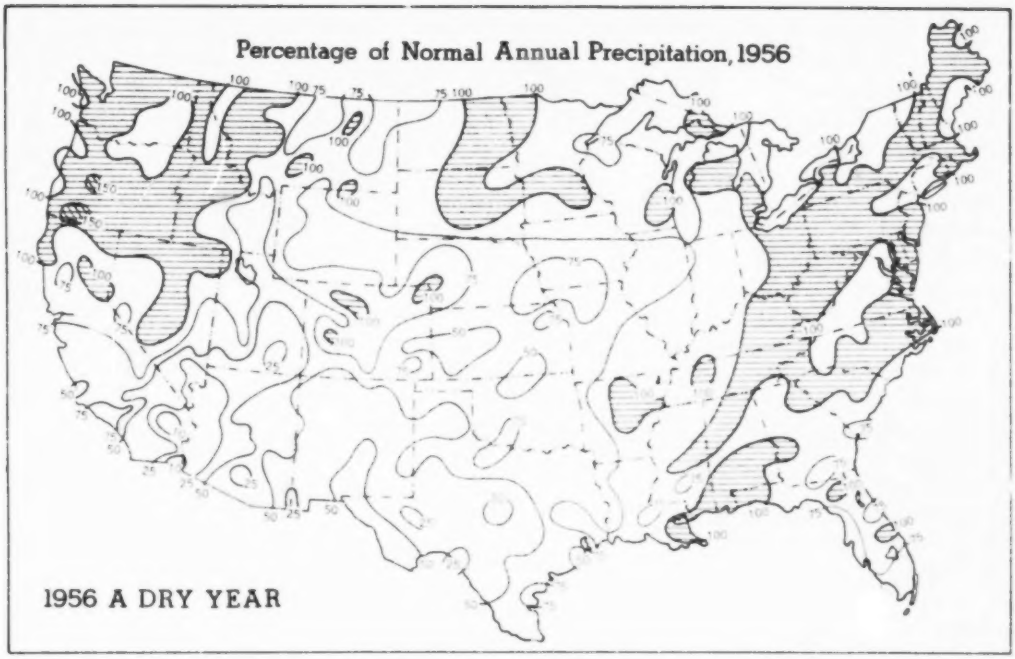

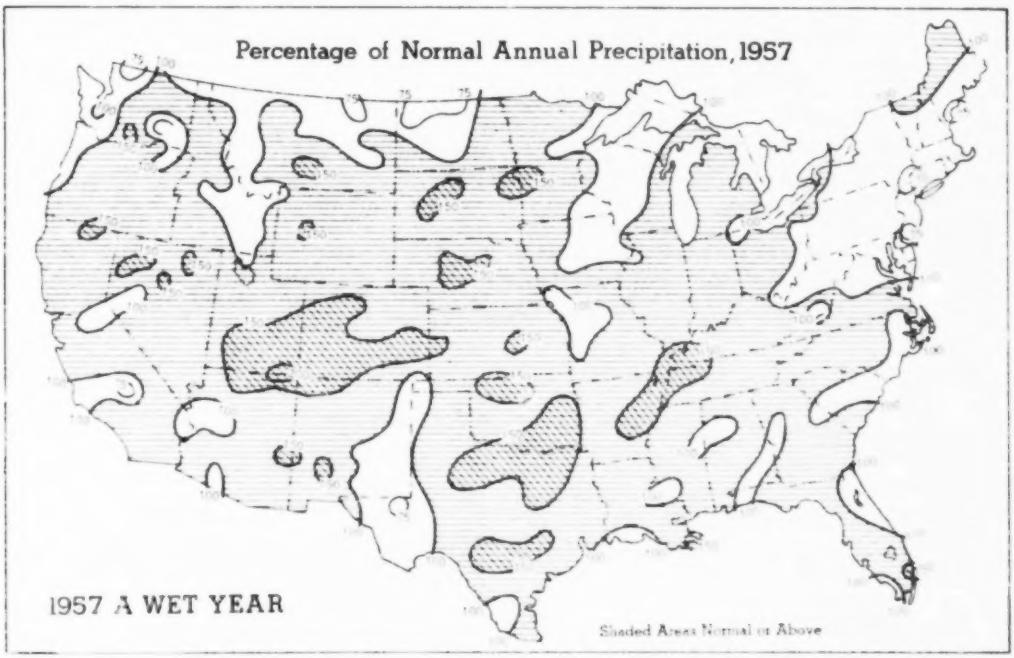

FIGURE 6.—Five years of drought in the southwestern United States was at peak severity in 1956. In the spring of 1957, severe floods occurred in the area where the drought had been most prevalent. The natural causes of such large-scale shifts in precipitation patterns should be better understood in order to determine how and to what extent they might be modified artificially.

the last ice age when glacial accumulations covered great parts of Europe and North America, and probably many other lands. A long continued warming or cooling of the earth by an amount averaging only 5° would greatly modify the water resources of the nations and fundamentally change the agricultural and industrial economies of the world. It is well known that changes in the average temperature of continents from year to year are associated with changes in the average paths of storms which bring most of the rain and snow, and it is quite certain that prolonged change in the average temperature of the earth would bring shifts in storm paths which would cause droughts in many regions that now have abundant rainfall. The humid air masses would drop their moisture in some cases on lands now deficient in precipitation. If the earth's average temperature were to drop 5° or 10°, the water of the oceans would become colder, there would be less evaporation from their surfaces and the total precipitation to fall on the earth would be less. The global hydrologic cycle would become less active. However, temperature records during the last 50 to 100 years indicate fairly definitely that the earth is now getting warmer at a rate equivalent to about 1.5° F. per century. This has been due primarily to warmer winters during the last 50 years, particularly at higher latitudes. So far, no basis has been found for conclusions as to whether this warming trend is about to end or whether it will continue indefinitely. The ultimate natural controls that govern these changes are not yet known.

Ewing and Donn have recently proposed a very interesting hypothesis to explain the ice ages in the Northern Hemisphere. (See reference 32.) Scientists at various times have theorized that changes in the temperature of the earth over long periods have been due to changes in solar radiation, that is, in the total heat received from the sun. Other hypotheses include the possibility that greater volcanic action in prehistoric times more or less continuously discharged great quantities of fine ash into the high atmosphere where it remained suspended between eruptions and absorbed or reflected the sun's rays so that the earth's radiation balance was changed and the surface cooled. Vast clouds of interstellar dust might account for similar effects. Another theory is that the carbon dioxide content of the atmosphere has varied over the millenia and that as result of the absorption characteristics of this gas it has acted like the glass of a greenhouse and caused the earth's surface to grow warmer until such time as the carbon dioxide content of the air was again reduced through one cause or another. With reference to this latter theory a few scientists have suggested that the present warming of the earth is due to increase in carbon dioxide content of the atmosphere, which itself may be a result of the great increase in oxidation of carbon by combustion of fuels for home and industry during the past century. It is pointed out that during the 20th century most of the fossil fuels (hydrocarbons) laid down by nature through many millions of years will have been burned up by industrial and home uses. Although records of carbon dioxide content of the atmosphere are not sufficiently long in time to give a good basis for evaluation of this theory and the figures available on fuel consumption do not fully support the theory, it is nevertheless of interest and indicative of the possibilities and the results that should be given consideration in studies of man's modification of climate.

These brief remarks about natural controls of weather and climate are in no sense a complete treatment of present knowledge of the subject. Meteorologists know much about the immediate or proximate controls of weather but this knowledge is descriptive rather than analytical in the sense of setting forth the absolute or ultimate causes. The remarks in the preceding paragraph show that up to the present time little is known with certainty about the ultimate causes. Extensive studies of the width and character of tree rings in forests with centuries of growth, and of differences in the strata found in glaciers and ocean bottoms, and of other evidence in geological formations, etc., reveal variations which reflect more or less the influence of climate and its changes. Even these extensive studies still have not disclosed much about the ultimate natural controls that determine weather and climate but they clearly show the importance of further research. Without a better understanding of cause and effect in the atmosphere there is little hope of intelligent planning for large scale modification of weather and climate for the purposes of increasing the total water resources of the nations.

Large-scale tests involve sequence of events.—Suggestions have been offered by scientists and others for testing some of the theories on large scale weather modification designed primarily for increasing rainfall and adding to national water resources. These suggestions refer to many different approaches, some of them now within the practical capabilities of man, others requiring such huge expenditure of effort and material that they are beyond practical reach, at least until the meteorological events which they would set off in sequence are better known and the ultimate benefits more certain in relation to the cost. Without going into discussion in this brief report it may be mentioned that among the various suggestions are the following: Construct great dams or barriers which would deflect warm, moist ocean currents toward the shores of arid lands thus giving a source of evaporation of moisture which might be carried by the winds and provide more rain over the land. Scatter great expanses of the tropical oceans with dyestuff that would increase absorption of the sun's rays, warm the water and cause more evaporation thus putting more moisture into the air to be carried by the winds and deposited as rain over the land. Use of other substances to increase evaporation from the oceans has been suggested. On the other hand, still other substances have been proposed to restrain evaporation from fresh water lakes and irrigation reservoirs. This latter appears to be a localized method that promises good results. It should have more research. Carbon black and other materials to absorb more radiation have been suggested for widespread coverage of polar ice or to be spread as fine dust suspended in the atmosphere over the poles during the respective daylight seasons in order to warm polar regions.

These proposals need to be studied more thoroughly to determine their ultimate consequences. Preliminary studies indicate that some of them and perhaps all would set off sequences of events which would miss the goal and in some cases bring new conditions that would make the cure "worse than the disease." Perhaps the best illustration of the last mentioned kind of consequences is the inevitable result of melting all of the ice in the Arctic. It would raise sea level sufficiently to submerge many of the major seaports throughout the world. If the earth is ever warmed sufficiently to melt all of the ice in the Antarctic as well, the level of the sea would rise more than 100 feet according to recent estimates based on ice measurements during the International Geophysical Year. For more information, see some of the studies given in the references 33 through 37.

With reference to proposals to increase the total rainfall by evaporating more water from the oceans aside from the enormity of the undertaking and the unsolved difficulty of relying on the winds to carry the moisture to the desired regions and find a precipitating mechanism there that would cause the moisture to fall as rain or snow, there is the problem of high humidity as an element in formation of destructive storms like hurricanes, tornadoes, hailstorms, etc. Any method for increasing rainfall and national water supply by increasing the moisture content of the atmosphere in general should be designed at the same time to control or dispel these violent kinds of storms. Fundamental research in the causes and behavior of these storms is in progress and should eventually reveal whether there are practical possibilities for controlling or dispelling them, but the solution is not yet in sight. New approaches to identifying some of the crucial factors influencing large-scale weather events are in prospect through the use of observing platforms such as rockets and satellites. Figure 7 is an example of the global view of cloud and storm systems which meteorologists hope will become increasingly available. These and related technological developments may lead to the discovery of important clues.

In general the methods proposed for large-scale shifts in rainfall patterns would, if successful, result in changing the normal regimes of climate and thus interfere with water resources essential to the established economy of other regions. It is conceivable that research may eventually show how to deflect air masses and winds so that rain that would normally fall over the oceans or over lands which now receive excess of rainfall would be directed to arid lands but up to the present time no scientist has suggested the slightest clue as to how this degree of control could be attained in practice nor have methods been proposed for preventing the inevitable undesirable consequences. Only further research will give the knowledge necessary to evaluation of the possibilities.

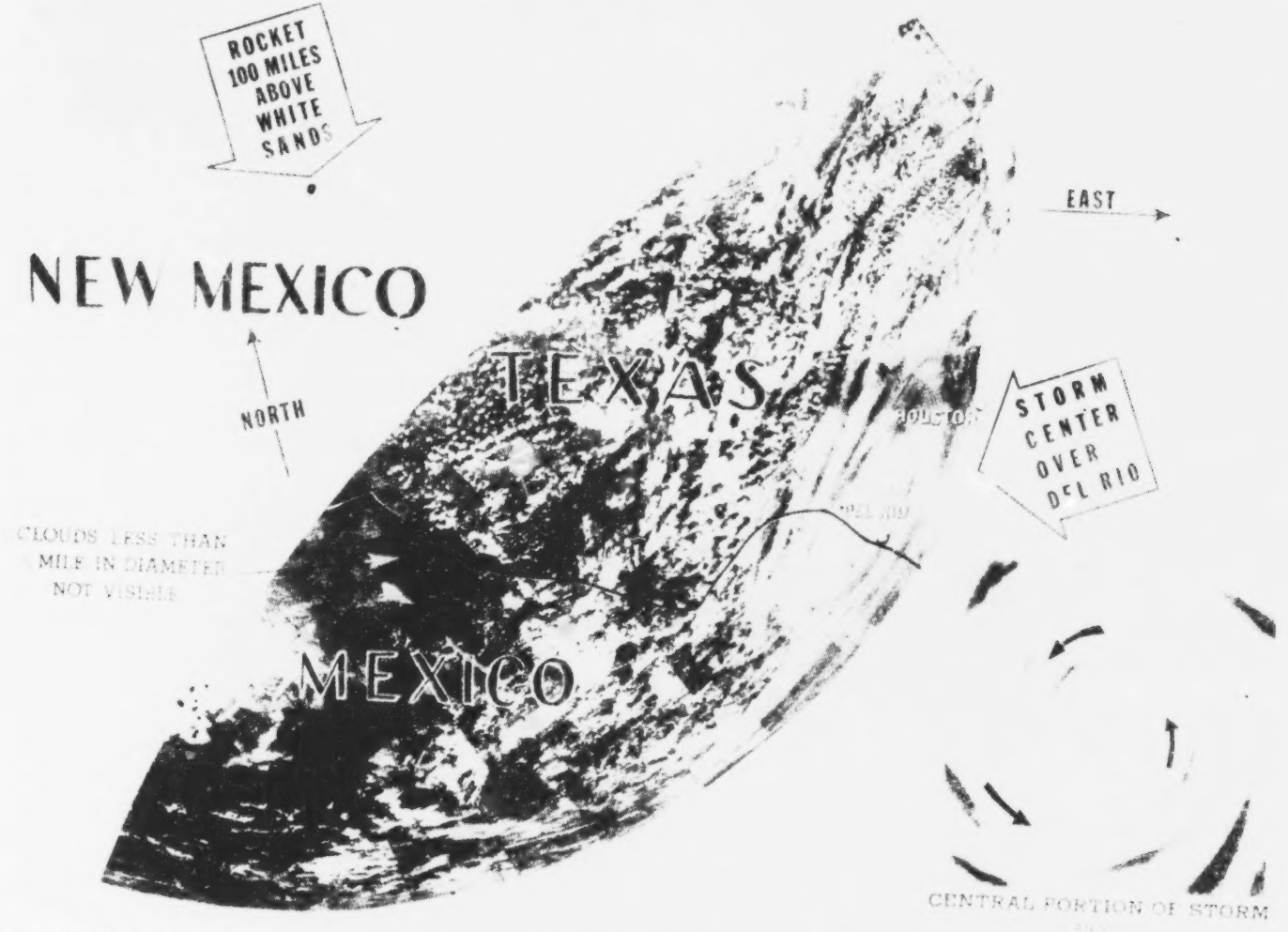

FIGURE 7.—Rocket and satellite photographs of the type analyzed by the Weather Bureau Meteorological Satellite Section will be useful in studies of global distribution of clouds and the evolution of cloud systems and major storms—Phenomena that must be taken into consideration in studies of large-scale weather modification.

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Other forms of limited weather modification.—While it is beyond the scope of this report to catalog all of the forms of weather modification that are to be considered, it should not be overlooked that certain limited controls of various meteorological conditions have been successfully practiced for many years. These include the heating of orchards under suitable conditions of temperature inversions to prevent frost, clearing of subcooled fog from airports by seeding with solid carbon dioxide, and other local methods for changing the natural distribution of temperature, humidity, wind, etc. Tree belts have been used successfully to retard runoff from rains, although reforestation has never been on sufficiently large scale to cause much change in atmospheric conditions in general. The natural conditions which determine the characteristics of air masses and fronts are very large by comparison and have not been greatly changed by the relatively small modification produced by changes made so far by man in the covering of the earth's surface whether by forests, vegetation, artificial lakes, etc. The weather effects of these manmade changes have been local only, and there is no immediate prospect that artificial changes with these comparatively limited dimensions could be used to modify weather on a scale sufficient to add materially to the Nation's water resources except as they may be designed to preserve or store the rainfall otherwise available.

CHANGES IN OUTLOOK

In his letter requesting this report by the Weather Bureau the chairman asked for comments on any changes in outlook with respect to weather modification. From the beginning there have naturally been many different individual views on the possibilities of weather modification and control of climate. At one time there were many who publicly expressed confidence that large increases in rainfall would at once be brought about by cloud seeding. There were others who expressed doubt on the entire subject of large-scale rainmaking. As stated in some of the preceding paragraphs and implied in the statements in other paragraphs, research and experimentation of the last decade indicated that the former were too optimistic and the latter not optimistic enough. The shifts in outlook appear to have been mostly toward the conclusions expressed by the ACWC, AMS, and WMO on pages 3 to 6. In short, the consensus now seems to be that although little success has been demonstrated in rainmaking up to the present time, there are promising though geographically limited possibilities to be explored, and there is great need for fundamental research and practical development to bring out these possibilities.

In fairness to scientists who from the beginning held substantially the views expressed in the conclusions by the ACWC, the AMS, and the WMO, it should be stated that many of them urged immediate expansion in basic research so that whatever possibilities there may be in weather modification would be determined and developed as rapidly as possible. The Weather Bureau has recommended annually in its budget since 1949, and in its communications to Congress that the basic research in this subject be strengthened.

The most significant change in outlook on weather modification in recent years has been the shift of emphasis and support from the expectation of immediate practical results to the need for basic research. If this program had been adopted when first advised, the knowledge of how and to what extent the weather can be modified with beneficial results would be many years ahead of its present stage. With specific reference to what this implies in planning the Nation's water resources, there are brief recommendations under the heading of the later section on "Future Prospects."

FURTHER RESEARCH

If the committee in its interest in national water resources wishes to know why a report on weather modification contains frequent reference to fundamental research in meteorology, the reason is to be found in the close relationship between weather modification on a large scale and the general circulation of the atmosphere. Previous conclusions have implied how difficult it is to devise successful techniques for rainmaking and other forms of weather modification and how impossible it is to analyze and evaluate the results as long as knowledge is so incomplete as regards many of the fundamentals in cloud physics and other phenomena involved in the causes of weather and climate. An understanding of the general circulation of the atmosphere and its secondary cyclones

and smaller circulations and the comprehensive physics of condensation and precipitation holds the key to the possibilities of weather modification. This knowledge would provide in addition many advances in techniques for prediction of weather and warnings of severe storms. While it is true that cloud seeding and inducement of rain locally might be developed without such comprehensive knowledge of meteorology as a whole, and might be applied through limited experiments and empirical principles, the results would be uncertain and unpredictable on the whole. Moreover, there are some indications that even local seeding may require an individual diagnosis of each cloud system to identify the particular circumstances and deficiencies in each case in order to apply the seeding treatment needed for success in the individual case. In other words, it is unlikely that any one seeding technique will be effective for all types of clouds. It is unlikely also that one experimental design will be applicable to all geographical regions with their differing meteorological conditions. Selection of the right design and the right technique involves knowledge of cloud physics.

During the last few years foundations have been laid for very extensive research in the atmospheric sciences. In view of the growing need for increase in the number of research scientists in this field and the importance of broadening the scientific base, the National Academy of Sciences, on recommendation by the Weather Bureau, appointed a Committee on Meteorology now called the Committee on Atmospheric Sciences (NAS/CAS). The farsighted recommendations of this Committee for recruitment and training of scientists in this field and for establishment of a National Institute for Atmospheric Sciences are contained in references 38 and 39.

Many research activities.—The report of the NAS/CAS cited above led to establishment of a University Committee on Atmospheric Research which is devoted to development of research programs. The research program of the National Science Foundation has been noted in an earlier paragraph. The list of its projects in weather modification and atmospheric sciences as of early 1959 is contained in appendix A. Additional proposals adopted by the end of fiscal year 1959 are contained in appendix B, and projects by other Federal agencies that are directly related to weather modification are listed in appendix C.

Weather Bureau research.—Among the research programs now in operation which relate directly although not exclusively to knowledge required for design of techniques for weather modification are:

General circulation project.—Comprehensive studies of atmospheric energy relationships and their basic roles in large-scale air movements, storm formation, dissipation, etc. Simulation of atmospheric behavior through the use of electronic computer techniques should ultimately permit laboratory-scale experiments on the feasibility and consequences of large-scale weather modification proposals.

National hurricane research project.—Detailed observations, measurements, and analyses of hurricane characteristics, behavior, and the forces and processes governing their origin, movement, intensification and decay. The research objectives include experimental use of cloud-seeding techniques and their evaluation.

Numerical weather prediction.—Systematic development and application of the newest mathematical and physical concepts together with electronic computational techniques for calculating weather developments from day to day. Progress in the use of these modern techniques for weather forecasting is an important requirement for objective evaluation of weather modification techniques, especially on a more local or intermediate scale.

Physical research program.—Basic laboratory and field studies including cloud and atmospheric electrification, droplet formation, and raindrop growth to formulate a more detailed and exact understanding of natural processes causing rain, snow, and hail and their possible modification with artificial techniques.

Meteorological satellite research program.—Development and uses of new observing and measuring tools from rockets and satellites. The research underway in collaboration with the National Aeronautics and Space Administration includes such major projects as cloud and storm census studies and detailed investigations of incoming and outgoing radiation. The latter is one of the fundamental and least understood factors involved in the possibilities of large-scale weather modification.

Severe storm research.—Studies of the causes and characteristics of dangerous storms with particular emphasis on squall lines, severe thunderstorms, hailstorms, and tornadoes and their prediction. Serious proposals for modifying such storms depend on a much more complete understanding of their nature, structure and "triggering" mechanisms.

Further proposals.—In order to survey the scope of the general problem of weather modification, the Weather Bureau several years ago itemized the subjects comprising a comprehensive program. These items first prepared in 1951 are still indic-

ative of the research involved in the general subject. The up-to-date list follows:

A Comprehensive Plan for Studies in Weather Modification

I. Data collection (field projects)

A. Diffusion of nucleating agents:
1. Investigations of optimum methods for release of seeding agents.
2. Studies of "targeting" of seeding plume.
3. Evaluations of feasibility of increasing freezing nuclei concentrations at cloud levels.
4. Investigations of effect of wind velocity profiles and temperature lapse rates on diffusion.
5. Tracer studies with zinc sulfide.

B. Effects of ground seeding on cloud structure:
1. Investigations of changes in subcooled water concentrations in clouds attributable to ground seeding.
2. Investigations of seeding rates necessary for complete nucleation in mountain crest clouds.

C. Cloud census studies:
1. First phase:
(*a*) Establish several special observation teams to obtain inventories of cloud development, precipitation and dissipation processes
(*b*) Obtain radar and optical-photographic measurements of—
(1) Precipitation initiation in relation to cloud dimensions, height of freezing level, rate of development and synoptic conditions.
(2) Frequency of precipitation occurrences in relation to total number of cloud formations.
2. Second phase:
(*a*) Evaluations of changes in cloud characteristics and precipitation occurrences during seeding operations based on comparisons with observations obtained during first phase.

D. Rainfall modification:
1. Establishment of cloud nucleation program over hydroelectric catchment area and suitable river basin (plans contingent upon results of projects I–A, I–B).
2. Tests of effectiveness of seeding by—
(*a*) Radar observations.
(*b*) Comparison of precipitation and runoff with historical and control data.
(*c*) Randomized seeding operations.
(*d*) Aircraft cloud surveys. (See project I–E.)
(*e*) Studies of rainfall distribution and raindrop spectra.

E. Aircraft investigations:
1. Cloud surveys with at least two aircraft over target area to determine seedability of cloud systems (in connection with project I–D).
2. Investigations of cloud distribution, type, and structure in cyclones affecting target area.
3. Collection of cloud particle samples for chemical analysis.
4. Spot seeding with CO_2, AgI, H_2O and NaCl to be evaluated by radar and visual observations.
5. Cloud physics measurements:
(*a*) Liquid water concentrations.
(*b*) Drop size measurements.
(*c*) Ice crystal sampling (for identification of nucleus with electron microscope and tests of spontaneous freezing temperature).
(*d*) Condensation nuclei measurements, i. e., salt particle sampling.
(*e*) Freezing nuclei.
(*f*) Humidity measurements, particularly in ice crystal clouds.

F. Specialized local applications:
1. Individual agency projects having a relationship to the general problems and possibilities of weather modifications of all kinds (Agriculture; Interior; Health, Education, and Welfare; Defense, etc.).
(*a*) Lightning and hail suppression (contingent upon indications from projects I–A, B, and C).
(*b*) Local shower modification for basin or reservoir catchment, snowpack increasing, etc.
(*c*) Dispersal of atmospheric pollutants via temperature inversion modification.
(*d*) Cloud and fog dissipation.

II. Research and development (laboratory and pilot studies)

A. Cloud particle growth mechanisms:
1. Experimental and theoretical studies of condensation and coalescence processes.
2. Ice crystal growth, clumping and fragmentation.
3. Effects of atmospheric electricity on cloud particle growth.

B. Atmospheric nuclei studies:
1. Studies of the nature, source, efficiency and natural concentrations of condensation and freezing nuclei.

C. Synoptic-climatic studies of precipitable cloud moisture:
1. Use of aircraft icing statistics and observations to establish preferred sectors of storm areas for application of artificial freezing agents.
2. Analyses of available liquid water content data and low-level humidity measurements as a means of evaluating "seeding potential."

D. Instrument development:
1. Airborne techniques for accurate measurements of liquid water content in warm and subcooled clouds.
2. Methods for measurement of ice crystal concentration in clouds.
3. Development of practicable nuclei detection and counting devices.
4. Airborne techniques for accurate measurement of humidity in clouds, e.g., infrared hygrometers, etc.
5. Application of radar to cloud physics and precipitation measurements.

E. Systems evaluations:
1. Use of numerical weather prediction and other physical models for evaluation of weather modification.
2. Investigations of the use of mechanical means and high energy sources for forced convection.
a. Climatology of atmospheric instability.
3. Investigations of the use of hygroscopic nuclei or other means for encouraging the formation of dew for agricultural applications.
4. Use of chemicals to inhibit or facilitate evaporation from water and plant surfaces.
5. Use of smoke palls to influence radiation heat losses or gains.

F. Search for other means of local weather modification:
1. Fog dispersal.
2. Local temperature inversion heating.
3. Initiation, deflection or modification of local wind systems.
4. Dew and other local condensation catchment.
5. Local shower analysis for basin or reservoir catchment.

III. DATA PROCESSING AND EVALUATION

A. Data processing:
1. Assemble, edit, and plot experimental data.

B. Data evaluation:
1. Statistical analysis.
2. Physical interpretation.
3. Evaluation of results.

C. Publication of results:
1. Preparation and drafting of diagrams and reports of research for publication.
2. Interim publications for limited distribution.
3. Preparation, editing, and publication of final project reports and conclusions.

FUTURE PROSPECTS

In his request for this report the chairman of the select committee asked for comments on future prospects for weather modification as a means of adding to the Nation's water resources. Senate Resolution No. 48 (Rept. No. 190), 86th Congress, referred to prospects as they might appear for the year 1980. In the present state of knowledge of the atmospheric sciences and the incomplete understanding of the ultimate causes of weather and climate brought out in many of the preceding paragraphs of this report, it is obvious that there is no basis even for a guess on the practical applications in the year 1980 of weather modification as a means of increasing national water resources. The situation is not greatly unlike the case of "atomic energy" if, in 1940, shortly after the first realization of the possibility of atomic fission, physicists had been asked to foresee its applications in 1960. They could hardly have come close to knowing the developments of the past 20 years! At present, among the few definite conclusions of a general nature that are justified with respect to weather modification and water supply, are the following:

1. Undoubtedly there are practical possibilities in weather modification which should be developed, but how widely they may be applicable and how much they will contribute to water supply, cannot now be foreseen with any degree of certainty.

2. Weather modification is unlikely ever to be a universal solution to shortage of natural water supply. It is unlikely to be a means for relieving general drought or providing water artificially for converting deserts to regions with adequate rainfall.

3. With respect to the chairman's inquiry about the best means for assuring the most rapid progress, the conclusions of the past 10 years of experimentation emphasize that fundamental research in the atmospheric sciences is not only the best approach but also the only approach that will provide comprehensive answers to the questions involved in weather modification and knowledge with which to design sound techniques. The research programs suggested by the several interested organizations in the paragraphs under further research appear to offer a sound general approach.

(NOTE.—Weather modification is inherently tied in with the winds, the movements of air masses, and the various circulatory systems of the atmosphere, large, intermediate, and small scale. The subject involves cloud physics and related phenomena, and possibly extraterrestrial considerations. The interrelationships of these things in the mechanisms of the atmosphere which produce the conditions we call weather and climate are among the most fascinating and complex subjects to be found anywhere. The scientific literature contains many excellent technical articles on these subjects, not only with respect to their roles as discrete phenomena but also in their interrelationships. It is beyond the purpose of this report to review the subject matter of the numerous technical papers dealing with these details in the science of meteorology and its possible applications in weather modification. Readers interested in more information will find much value in the references, and those who read can hardly fail to be impressed by the great amount of research to be done and knowledge yet to be gained before the full potentialities of weather modification and its consequences can be understood and intelligently applied.)

BIBLIOGRAPHY

This listing contains only a small sampling of the many publications in the field of weather modification and related subjects. More extensive bibliographies may be found in the March 1950, July 1954, and October 1955 issues of Meteorological Abstracts and Bibliography, published by the American Meteorological Society, and in

volume II of the "Final Report of the Advisory Committee on Weather Control," pages 322–396.

REFERENCES CITED IN TEXT

1. Abbe, Cleveland, "Artificial Rain." Monthly Weather Review, vol. 28, No. 1, January 1900, pp. 22–23.
2. Humphreys, W. J., "Rainmaking and Other Weather Vagaries." Baltimore, Williams & Wilkins Co., 1926.
3. U.S. Senate, "Report of the Secretary of Agriculture for Making Experiments in the Production of Rainfall." Senate Executive Document No. 45, 52d Congress, 1st session, vol. 5, p. 57.
4. Veraart, A. W., "Meer Zonneschijn in Het Nevelig Noorden, Meer Regen in de Tropen" (More Sunshine in the Cloudy North, More Rain in the Tropics). N. V. Seyffardt's Boek en Muziekhandel, Amsterdam, 1931.
5. Veraart, A. W., "Aan Zijne Excellentie den Minister van Onderwijs, Kunsten en Wetenschappen", 's-Gravenhage, Rijswijk, Nov. 9, 1931.
6. Veraart, A. W., "Records van Zonneschijn en regen in 1930." 's-Gravenhage, H. J. T. Matveld, 1932 (Rede gehouden voor de K. R. O. Microfoon op Zondag 29 Mei, 1932).
7. Veraart, A. W., "Report on Heavy Rainfall of October 6, 7, 1930." Natuur en Techniek, vol. 1, August 1931.
8. Langmuir, I., Schaefer, V. J., and others, "First Quarterly Report, Meteorological Research," General Electric Research Laboratory, July 15, 1947.
9. Schaefer, V. J., "Final Report, Project Cirrus, Part I: Laboratory, Field, and Flight Experiments." Report No. RL 785, General Electric Research Laboratory, March 1953.
10. "Final Report of Advisory Committee on Weather Control," U.S. Government Printing Office, December 1957.
11. American Meteorological Society, "Statement on Weather Modification." Bulletin of the American Meteorological Society, vol. 38, No. 6, June 1957, p. 366.
12. World Meteorological Organization, "Artificial Control of Clouds and Hydrometeors." Technical Note No. 13, 1955.
13. Bowen, E. G., "A New Method of Stimulating Convective Clouds To Produce Rain and Hail." Quarterly Journal of the Royal Meteorological Society, vol. 78, No. 335, January 1952, pp. 37–45.
14. Brazell, J. H., and Taylor, C. M., "Artificial Stimulation of Rainfall in East Africa by Means of Rockets." Memoirs, East African Meteorological Department, vol. III, No. 6, 1959.
15. Fournier d'Albe, E. M., "Cloud-Seeding Trials Using Common Salt." "Artificial Stimulation of Rain" (Proceedings of the First Conference on the Physics of Cloud and Precipitation Particles, Woods Hole Oceanographic Institution, Sept. 7–10, 1955) Pergamon Press, 1957.
16. Fuquay, D. M., "Generator Technology for Cloud Seeding." Paper presented at Joint Conference on Weather Modification sponsored by American Society of Civil Engineers and American Meteorological Society, Denver, Colo., Aug. 27–29, 1959.
17. Fuquay, D. M. and Wells, H. J., "The Project Skyfire Cloud-Seeding Generator." Research Paper No. 48, Intermountain Forest and Range Experiment Station, U.S. Department of Agriculture, 1957.
18. Smith, R. B. and others, "Modification of Fog and Cloud Particles in the Atmosphere." AFCRC-TR-59-228 (ASTIA-AD 212 553), Mar. 31, 1959.
19. van Straten, F. W., and others, "Preliminary Experiments Using Carbon Black for Cloud Modification and Formation." Report No. 5235, U.S. Naval Research Laboratory, Washington, D.C., Oct. 28, 1958.
20. Vonnegut, B., "Techniques for Generating Silver Iodide Smokes." Journal of Colloid Science, vol. 5, No. 37, 1950.
21. Battan, L. J., and Kassander, A. R., Jr., "Artificial Nucleation of Orographic Cumuli." Paper presented at Conference on Physics of Precipitation, Woods Hole Oceanographic Institution, June 1959.
22. "National Science Foundation Announces $1,130,000 Research Program on Weather Modification." Bulletin of the American Meteorological Society, vol. 40, No. 5, May 1959, p. 263.
23. Braham, R. R., and Neil, E. A., "Modification of Hurricanes Through Cloud Seeding," National Hurricane Research Project Report No. 16 (a preprinted report).
24. Battan, L. J., "Cloud-Physics Research in the Soviet Union." Bulletin of the American Meteorological Society, vol. 40, No. 9, September 1959, pp. 444–464.
25. World Meteorological Organization, "Artificial Control of Clouds and Hydrometeors (Provisional Report of Working Group)," WMO Bulletin, vol. VIII, No. 3, July 1959, pp. 140–144.
26. Oddie, B. C. V., "First Results of the Meteorological Office Experiments on the Artificial Stimulation of Rainfall." The Meteorological magazine, vol. 88, No. 1043, May 1959, pp. 129–135.
27. Bowen, E. G., and others, The Australian Reports. "Final Report of the Advisory Committee on Weather Control," vol. II, pp. 290–299.
28. Sanger, R., "The Swiss Randomized Hail Suppression Experiment in the Tessin," paper presented at Conference on the Physics of Precipitation, Woods Hole Oceanographic Institution, June 1959.
29. Dessens, H., "A Project for a Formation of Cumulonimbus by Artificial Convection," paper presented at Conference on the Physics of Precipitation, Woods Hole Oceanographic Institution, June 1959.
30. Balabanova, V. N., and others, "Some Results of Experimental Seeding of Cumulus Clouds in Alazansk Valley in Georgian (Gruzian) S.S.R.," Journal of the Academy of Science U.S.S.R., Geophysical Series (Izvestia Akademii Nauk, seriia Geofizicheskiia), February 1959, pp. 262–275.

31. Brier, G. W., "Seven-Day Periodicities in Certain Meteorological Parameters During the Period 1899–1951." Bulletin of the American Meterological Society, vol. 36, No. 6, June 1955, pp. 265–277.
32. Ewing, M. and Donn, W. L., "A Theory of the Ice Ages." Science, vol. 123, No. 3207, June 15, 1956, pp. 1061–1066.
33. Wexler, H., "Modifying Weather on a Large Scale." Science, vol. 128, Oct. 31, 1958, pp. 1059–1063.
34. Wexler, H., "A Warming Trend at Little America." Weather, vol. XIV, No. 6, June 1959, pp. 191–197.
35. Ahlmann, H. W:son, "The Present Climatic Fluctuation." Geographical Journal, vol. CXII, Nos. 4–6, 1948, pp. 165–195.
36. Chubukov, L. A., and others, "Changes in Arctic Climate," Komsomal'skaya Pravda, July 26, 1959 (translation in Information on Soviet Bloc International Geophysical Cooperation 1959, Office of Technical Services, U.S. Department of Commerce, Oct. 2, 1959).
37. Willett, H. C., "Temperature Trends of the Past Century," Centenary Proceedings of the Royal Meteorological Society, 1950, pp. 195–206.
38. Committee on Meteorology, "Research and Education in Meteorology." An Interim Report of the Committee on Meteorology to the National Academy of Sciences, National Research Council, Washington, D.C., Jan. 25, 1958.
39. University Committee on Atmospheric Research, "Preliminary Plans for a National Institute for Atmospheric Research," "Second Progress Report of the University Committee on Atmospheric Research" (prepared for the National Science Foundation), February 1959.

ADDITIONAL EVALUATIONS AND STUDIES NOT CITED IN THE TEXT

Ackerman, E. A., and Lof, G. O. G., "Increasing Soil Moisture, Runoff, and Percolating Waters through Weather Modification." Chapter 14 of "Technology in American Water Development," the Johns Hopkins Press, Baltimore, Md., 1959, pp. 356–383.

Anonymous, "Clouds Sprayed with Dry Ice Made to Yield Rain." Popular Mechanics, September 1930.

Anonymous, "On the Causes of Rain and the Possibility of Modifying Them by Art." Scientific American, vol. 8, No. 21, Feb. 5, 1853, p. 168.

Baum, W. A. and others, "Assessment of the Effect of Commercial Cloud Seeding in North Florida and South Georgia, 1955–1956." Quarterly Journal of the Florida Academy of Sciences, vol. 19, Nos. 2–3, June–September 1956, pp. 104–120.

Bergeron, T., "On the Physics of Cloud and Precipitation." Proces-Verbaux des seances d l'Assoc. de Met. de l'U.G.G.I. a Lisbonne, 1933, pt. II, Paris, 1935, pp. 156–178.

Bergeron, T., "The Problems of Artificial Control of Rainfall on the Globe, I. General Effect of Ice Nuclei in Clouds," Tellus, vol. 1, February 1955.

Berry, F. A., "Evaluation of Weather Modification Experiments." Journal American Water Works Association, vol. 48, No. 8, August 1956, pp. 973–981.

Braham, R. R., Jr., and Battan, L. J., "Effects of Seeding Cumulus Clouds." Journal American Water Works Association, vol. 50, No. 2, February 1958, pp. 185–192.

Brier, G. W. and Enger, I., "An Analysis of the Results of the 1951 Cloud Seeding Operations in Central Arizona." Bulletin of the American Meteorological Society, vol. 33, No. 5, May 1952, pp. 208–210.

Buell, E., "An Evaluation of the Results of Cloud Seeding in Western New Mexico and Southeastern Arizona during July and August 1951 and 1952." Bulletin of the American Meteorological Society, vol. 36, No. 1, January 1955, pp. 6–15.

Committee for Rain-Making in Japan. "Report of Rain-Making in Japan," vol. I, 1954.

Compania Mexicana de Luz y Fuerza Motriz, S. A., "Nueve Anos de Experiencias de Estimulacion de la Lluvia en la Cuenca Hidrologica de Necaxa." Informe, 1958.

Coons, R. D., and others, "First Partial Report on the Artificial Production of Precipitation: Stratiform Clouds, Ohio, 1948." "Research Paper No. 30," U.S. Weather Bureau, 1948. (Summary published in Bulletin of the American Meteorological Society, vol. 29, No. 10, December 1948, pp. 544–546.)

Coons, R. D., and others. "Artificial Production of Precipitation, Third Partial Report: Orographic Stratiform Clouds, California, 1949; Fourth Partial Report: Cumuliform Clouds, Gulf States, 1949." "Research Paper No. 33," U.S. Weather Bureau, September 1949. (Summaries published in Bulletin of the American Meteorological Society, vol. 30, No. 7, September 1949, pp. 255–256, and vol. 30, No. 8, October 1949, pp. 289–292).

Davies, D. A., and others, "Report on Experiments at Kongwa on Artificial Stimulation of Rain, January–April 1951." East African Meteorological Department Memoir, vol. II, No. 9, 1954.

Davies, D. A., and others, "Report on Experiments at Kongwa on Artificial Control of Rainfall, January–April 1952". East African Meteorological Department Memoir, vol. II, No. 10, 1954.

Davies, D. A., and others, "Report on Experiments on Artificial Control of Rainfall at Amboseli, Kenya, and Dodoma, Tanganyika, 1953–54." East African Meteorological Department Memoir, vol. III, No. 3, 1955.

Douglas, R. H., "A Statistical Analysis of the Results of Cloud Seeding in Quebec, 1951 and 1952." "CIR-2536, TEC-193," Meteorological Division, Department of Transport, Canada, September 1954.

du Chaxel, R., "Les Premieres Experiences de Pluie Artificielle en Afrique Equatoriale Francaise." French Equatorial Africa, Service Meteorologique, Publication No. 2, July 1955.

Espy, J. P., "Artificial Rains," "The National Gazette and Literary Register," Philadelphia, 19 (5798), Title page, April 5, 1839. Reprinted in his "Philosophy of Storms," Boston, 1841, pp. 492–500.

Eyraud, R., "La Pratique de la Pluie Artificielle." Memorial de la Meteorologie Nationale, No. 34, 1950.

Findeisen, W., "Die Kolloidmeteorologischen Vorgange bei der Niederschlagsbildung." Meteorologgische Zeitschrift, vol. 55, No. 4, April 1938, pp. 121–133. (English

translation, mimeographed, U.S. Weather Bureau Library, 1939.)

Findeisen, W., "Der Aufbau der Regenwolken." Zeitschrift für Angewandte Meteorologie das Wetter, vol. 55, No. 7, 1938, pp. 208–225. (English translation, mimeographed, U.S. Weather Bureau Library, 1939.)

Findeisen, W., "Meteorologisch-physikalische Begingtheiten der Vereisung in det Atmösphare." A paper before the 1938 Hauptversammlung der Lilienthal-Gesellschaft für Luftfahrtforschung. (English translation, mimeographed, U.S. Weather Bureau Library, 1939.)

Fournier d'Albe, E.M., and others, "The Cloud-Seeding Trials in the Central Punjab, July–September 1954." Quarterly Journal, Royal Meteorological Society, vol. 81, No. 350, 1955, pp. 574–581.

Gathmann, L., "Rain Produced at Will". Chicago, 1891.

Godson, W. L., "Report on Evaluation of Cloud-Seeding Operations in Manitoba," "CIR–2649, TEC–215", Meteorological Division, Department of Transport, Canada, May 2, 1955.

Hales, J. V., and others, "An Evaluation of the Effects of Cloud Seeding in Southern Utah, April 1951—November 1954." Bulletin of the University of Utah, vol. 46, No. 15, June 1955.

Hall, W. F., and others, "Cloud Seeding Operations in the Bishop Creek, Calif., Watershed." Research paper No. 36, U.S. Weather Bureau, January 1953. (Summary published in Bulletin of the American Meteorological Society. vol. 34, No. 3, March 1953, pp. 111–116.)

Hatakeyama, H., "Report of Rainmaking in Japan, 1954–56." Papers in Meteorology and Geophysics, Tokyo, vol. 7, No. 3, October 1956, p. 327.

Houghton, H. G., "An Appraisal of Cloud Seeding as a Means of Increasing Precipitation," Bulletin of the American Meteorological Society, vol. 32, No. 2, February 1951, pp. 39–46.

Houghton, H. G., "Cloud Physics." Science, vol. 129, No. 3345, February 6, 1959, pp. 307–313.

Houghton, H. G., "Present Position and Future Possibilities of Weather Control." Bulletin of the American Meteorological Society, vol. 38, No. 10, December 1957, pp. 567–570.

Lincoln, R. L., "Analysis of Four Years of Attempts to Increase Precipitation by Cloud Seeding in Tri-County Area, Oregon, 1950–1954." "Miscellaneous Paper No. 10," Agricultural Experiment Station, Oregon State College, Corvallis, 1955. (Summary published in Bulletin of the American Meteorological Society, vol. 38, No. 3, March 1957, pp. 134–137.)

Ludlam, F. H., "Artificial Snowfall from Mountain Clouds," Tellus, vol. 7, No. 3, August 1955, pp. 277–289.

Malone, T. F., "A National Institute for Atmospheric Research", Transactions, American Geophysical Union, vol. 40, No. 2, June 1959, pp. 95–111.

Mason, B. J., "Design and Evaluation of Large-Scale Rain-Making Experiments," Nature, vol. 175, No. 4454, March 12, 1955.

Mason, B. J., "Recent Developments in the Physics of Rain and Rainmaking." Weather, vol. XIV, No. 3, March 1959, pp. 81–97.

Mason, B. J., "Artificial Stimulation of Precipitation," "The Physics of Clouds," Oxford University Press, 1957, pp. 268–305.

McDonald, J. E., "Scientific Basis of Weather Modification," Science, vol. 124, No. 3211, July 13, 1956, pp. 86–87.

McDonald, J. E., "The Physics of Cloud Modification," Advances in Geophysics, vol. 5, Academic Press, Inc., pp. 223–303.

National Academy of Sciences, "On the Design and Conduct of Research Programs in Weather Modification," Report of the Skyline Conference, Division of Mathematics, National Academy of Science-National Research Council (in preparation).

Orr, J. L., and others, "Canadian Experiments on Artificially Inducing Precipitation." Bulletin of the American Meteorological Society, vol. 31, No. 2, February 1950, pp. 56–59.

Petterssen, S., and others, "Cloud and Weather Modification: A Group of Field Experiments." Meteorological Monographs, vol. 2, No. 11, American Meteorological Society July 1957.

Pire, J. J., "Essais de Pluies Artificielles a Temvo, Congo Belge en Mars 1954." Belgium, Academie Royale des Sciences Coloniales, vol. 25, No. 5, 1954, pp. 1560–1575.

Pire, J. J., "Essais de Stimulation Artificielle de la Pluie a Tely (Territoire de Poko, Congo Belge), Janvier 1955." Belgium, Academie Royale des Sciences Coloniales, Bulletin des Seances, N. S., vol. 2, No. 2, 1956, pp. 230–244.

Rain Stimulation Research Institute, "Second Report on Cloud Seeding Experiments over Sun Moen Lake Area, 1951–1954." Taipei, Taiwan, China, 1956.

Ramage, C. S. and Bell, G. J., "Artificial and Orographic Stimulation of Rainfall in Hong Kong." "Technical Note No. 13," Hong Kong Royal Observatory, 1955.

Sansom, H. W. and others, "Report on Experiments on Artificial Stimulation of Rainfall at Mityana, Uganda, September–December 1954." East African Meteorological Department Memoir, vol. III, No. 4, 1955.

Shaw, Napier, "The Artificial Control of Weather." Monthly Weather Review, vol. 49, April 1921, pp. 244–246.

Spar, S., "A Weather Control Experiment in the Eastern United States." Transactions of the New York Academy of Sciences, Ser. II, vol. 17, No. 8, June 1955, pp. 621–626.

State of California. "Weather Modification Operations in California." "Bulletin No. 16, State Water Resources Board," June 1955.

University of Chicago, "Cloud Physics and Rainmaking," 1957.

U.S. Department of the Interior. "Report on Bonneville Power Administration Cloud-Seeding Operations," July 1952.

Walden, C. C., and Cuthbert, R. M., "The Evaluation of Rainmaking Operations in British Columbia, Phase 2." The British Columbia Research Council, August 1957.

Warner, J., and Twomey, S., "The Use of Silver Iodide for Seeding Individual Clouds," Tellus, vol. 8, No. 4, November 1956, pp. 453–459.

APPENDIXES

APPENDIX A.—*National Science Foundation*

WEATHER MODIFICATION GRANTS AND CONTRACTS, ACTIVE AS OF FEB. 16, 1959

Project No.	Institution	Investigator	Title	Amount of grant
P-2862	University of California	Neyman, J	Randomized cloud seeding	$36,700
P-3409	University of Chicago	Byers, H	Detection of ice nucleating agents	81,000
P-3808	Northam Electronics	Bollay, E	Freezing nuclei research	30,000
P-4037	Meteor Research, Inc	MacCready, P	Santa Barbara project	9,300
P-4136	National Bureau of Standards	McMurdie	Silver iodide studies	20,000
P-4615	University of Arizona	Battan-Kassander	Seeding of summer cumulus clouds	22,200
P-4807	American Geophysical Union	Smith, Waldo	Conference on cloud physics, June 1959	25,000
Pe-5280	Foundation for Instrumentation Education and Research.	Slater	Pilot cross-disciplinary clinic on the instrumentation requirements for cloud and weather modification.	5,100
P-5298	Arthur D. Little, Inc	Vonnegut	Cloud electrification studies	50,000
P-4909	Meteorology Research, Inc	MacCready	Continued cloud physics and studies at Santa Barbara	40,000

ATMOSPHERIC GRANTS AND CONTRACTS (OTHER THAN WEATHER MODIFICATION), ACTIVE AS OF FEB. 16, 1959

P-2565	Pennsylvania State University	Hosler, C	Aggregation of ice crystals	$11,000
P-3114	University of Washington	Fleagle, R	Physics of atmospheric motions	12,400
P-3980	Texas A. & M. Research Foundation	Hood	Calcium equilibrium in sea water	10,000
P-3716	University of Michigan	Dingle	Raindrop size spectra	40,000
P-3669	University of California at Los Angeles	Neiburger	Cloud drop growth	64,750
P-4130	University of Wisconsin	Lettau	Convective energy transfer	22,000
P-4706	Massachusetts Institute of Technology	Houghton, H	Atmospheric research in the United States	52,400
P-3950	do	Willett, H. C	Solar activity on atmospheric circulation	26,000
P-4926	Oregon State College	Decker, Fred	Precipitation radar study	5,000
P-4323	University of Illinois	Semonin	Atmospheric particulates in precipitation physics	43,000
P-4577	University of Chicago	Newton, C	Analysis of extratropical systems	20,000
P-4087	do	Pettersen, S	Heat and water vapor exchange processes	37,500
P-5057	University of California, Scripps	Rakestraw	Carbon dioxide exchange, atmosphere-ocean	34,000

APPENDIX B.—*Other National Science Foundation grants in atmospheric sciences (including weather modification) during fiscal year 1959*

Project No.	Institution	Investigator	Title	Amount of grant
P-5332	Aerometric Research, Inc	Elliott	Investigation of precipitation processes and efficiency of Pacific coast storms.	$90,500
P-5422	University of Arizona	Kassander, Battan, McDonald.	Physics of clouds and of cloud modification	161,800
P-5442	Atmospheric Research Group	MacCready	Field studies in cloud physics	57,100
P-5979	University of California	Keeling	Meteorological aspects of carbon dioxide and its exchange with the ocean.	24,700
P-5978	do	Rakestraw	Carbon dioxide and its exchange with the ocean	26,900
P-5708	do	Neyman	Randomized cloud seeding	64,900
P-5053	do	Sekera	Planetary earth albedo	58,700
P-5092	University of Chicago	Byers	Research in cloud physics	383,700
P-5201	do	do	Physical effects of silver iodide seeding in the Great Plains	114,300
P-5434	Department of Commerce, Weather Bureau.	Kinzer	Electrical properties of the lower atmosphere	45,000
P-5415	do	Kline	Studies of freezing nuclei anomalies	68,900
P-6206	do	Reichelderfer	Arctic ice flow meteorology	13,300
P-5977	do	Landsberg	Atmospheric profiles	40,000
P-6130	do	Reichelderfer	Arctic Basin meteorology	34,500
303	do	Wexler	Antarctic troposphere and stratosphere structure	149,000
304	do	do	Atmospheric and oceanic circulation	77,000
Ps-5467	Massachusetts Institute of Technology	Houghton	Study of means for the augmentation of the national effort in atmospheric research.	50,000
P-5954	University of Minnesota	Freier	Electrical properties of the atmosphere	63,100
P-4908	Meteorology Research, Inc	MacCready	Cloud physics studies—Santa Barbara project	40,000
Pe-5818	National Academy of Sciences	Wilkes	Conference on the design and conduct of research programs in weather modification.	10,000
P-6080	National Bureau of Standards	Brown	Airglow photometer	5,000
P-5929	Nebraska State Teachers College	Andrews	Physical study of a hail suppression program	11,000
P-5505	New Mexico Institute of Mining and Technology.	Brook	Thunderstorm electrification	194,600
P-5503	do	Crozier	Study of atmospheric space charge	45,000
P-5697	New York University	Woodbury	A study of statistical evaluations of weather modification	58,800
P-5390	Oklahoma State University	Jones	Investigation of the electric field intensity near a severe storm	23,100
P-5158	Pennsylvania State University	Blackadar	Graphical integration of circulation models	13,300
P-5157	do	Hosler	The role of orographic barriers of less than 3,000 feet in the generation and propagation of showers.	98,600
P-5173	A. & M. College of Texas	Sasaki	A study of mesoscale disturbances in the atmosphere by numerical methods.	35,000
P-5116	do	Saucier	Stratospheric patterns	74,100
P-4842	Tufts University	Schell	Nature of climatic change	17,000
222.5	University of Wisconsin	Suomi	Energy budget of the earth	7,500
P-5305	Woods Hole Oceanographic Institution	Malkus	Atmospheric convection, and its role in tropical meteorology	156,100
P-5397	do	Woodcock	Sea-salt nuclei—their origin, physical-chemical nature and role in atmospheric processes.	83,100

APPENDIX C.—*Weather modification research being conducted by Federal agencies other than the National Science Foundation*

Name	Location	Investigator	Title	Estimated amount for fiscal year 1959
Department of Agriculture: Project Skyfire.	Missoula, Mont.	J. S. Barrows	Investigation of cloud modification techniques to the problem of lightning-caused forest fires.	$75,000
Department of Commerce, U.S. Weather Bureau: National hurricane research project.	West Palm Beach, Fla.	R. R. Braham (University of Chicago).	Hurricane cloud physics investigation.	[1] 53,500
	Washington, D.C.	D. B. Kline	Atmospheric ice nuclei observations	15,000
	Missoula, Mont., Santa Barbara, Calif.		Cooperating in outside cloud seeding projects.	[2] 5,000
Department of Defense, Army:				
3-99-04-11	Army Research and Development Laboratories, Fort Monmouth, N.J.		Cloud physics and cloud modification.	15,000
3-35-15-4.2	do.		Attenuation studies	15,000
Department of Defense, Navy:				
082-128	A. D. Little, Boston, Mass.	B. Vonnegut, C. Moore	Thunderstorm electrification	[3] 150,000
082-129	Cornell Aeronautical Laboratory	R. Pelle	Freezing rain	15,000
NA 910-073	Naval Research Laboratory, Washington, D.C.	J. E. Dinger	Cloud physics studies using carbon black, Project Blackbody.	50,000
Department of Defense, Air Force:				
7605	Geophysical Research Directorate, Cambridge, Mass.		Weather modification-dispersion or prevention of low clouds and fog at airfields.	75,000
6697	do.		Stratus and fog dissipation for operational support of transport and cargo aircraft.	[4] 100,000
7695	do.		Contrail suppression	50,000

[1] Aircraft and its support not included.
[2] Plus loan and transfer of equipment.
[3] Including NSF partial support.
[4] Planned.

NOTE.—Information compiled by the Interdepartmental Committee on Weather Modification, January 1959.

WEATHER MODIFICATION

PART 2

WEATHER MODIFICATION AS A NEW TECHNIQUE TO INCREASE WATER SUPPLIES

PREPARED BY
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FOREWORD

The Senate Select Committee on National Water Resources is seeking answers to some very perplexing problems concerning the water resources needs of the Nation between now and 1980. Everyone is mindful of the fact that with an increasing population and an expanding industrial production more water will be needed in the future to take care of these increased demands. The question to be answered can be stated in a very few words—"*How much additional water will be needed by the year 2000; where is it coming from?*"

One of the newer techniques that seems to offer possibilities in increasing the water supply is through weather modification, or commonly known as increasing the rainfall by the seeding of clouds.

Some of the work and findings of many of our scientists actively engaged in atmospheric physics and weather modification is herein reviewed in an attempt to find an answer to the question: Can weather modification be a means of increasing our water supply? This paper is prepared at the request of the select committee.

Work in this field is relatively new and consequently a great deal more needs to be known before a definite and conclusive answer can be given. I believe we can say, however, that today we find a great many of our scientists working in this field agreeing that clouds can be modified to produce additional rain by seeding them. This does not mean that workers in the field have all the answers. The knowledge and understanding of the atmosphere is just in its infancy. This paper explores some of the possible solutions in more or less nontechnical language.

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WEATHER MODIFICATION

Part 2

WEATHER MODIFICATION AS A NEW TECHNIQUE TO INCREASE WATER SUPPLIES

INTRODUCTION

Water in the air is an important resource. All water used by civilized man comes from atmospheric sources. It waters the land from precipitation that falls and it supplies the lakes and rivers. More than six times as much water flows across continental United States in the air as is carried by all the country's great rivers. About 99 percent of this atmospheric water flows in the invisible form ready to condense when conditions are right.

These air masses heavily laden with moisture moving from the Pacific Ocean east across the North American Continent leave the east coast with three-fourths of their original moisture. Nearly all the moisture that supplies rainfall over the eastern half of the United States comes from the Gulf of Mexico and the nearby Atlantic Ocean.

This atmospheric water is the most mobile part of all the earth's water supply. The recharge of water into the atmosphere is automatic. It takes place by evaporation of water from the ocean into the atmosphere (the hydrologic cycle) and by evapotranspiration from the land. For example two-thirds of the annual precipitation in the upper Missouri Valley comes from the ocean and one-third is reevaporated land precipitation. This extensive recirculation of water from the land to the atmosphere makes it possible to produce precipitation several times from the same air and vapor mass. Nature has a low efficiency of natural precipitation. It is estimated that 5 percent to 15 percent of the available moisture in a cloud system reaches the ground during a rainstorm.

The question arises, after reviewing all the facts, "Can weather modification, as a new technique furnish an additional supply of water to relieve, to some extent, the pressure that is developing upon our present visible supply?"

HOW PRECIPITATION IS PRODUCED NATURALLY

Clouds are composed of small droplets. They are about one-thousandth of an inch in diameter and are present in large numbers. On the other hand raindrops are much larger and therefore less numerous in a cloud. It takes about 1 to 8 million droplets to make a single raindrop. How does nature bring together all the necessary droplets to form one raindrop?

There are two main processes acting in nature. One is called the coalescence process where there is collision or joining together of the small droplets. This process calls for some droplets to be larger than others so in having a different motion, they collide and grow in size to a raindrop. The other process requires the presence of ice crystals which are small, flat and six sided—larger than droplets. These crystals collide with the droplets and grow into a granular shape and when large enough into snowflakes. As they fall they may turn to rain below the cloud depending on temperature.

WEATHER MODIFICATION

Some of the first scientific experiments to increase rainfall were started by Veraart (30) in Holland in 1930. Bergeron (35) in 1933 advanced the theory that rain in appreciable amounts could be released by ice crystals in or transported through subcooled water clouds. Some years later Fendeisen (47) substantiated the Bergeron theory by stating that the coexistence of ice crystals and supercooled water droplets in proper proportion is a necessary condition for the precipitation process to start. The Bergeron-Fendeisen theory is the basis for present day techniques of weather modification in midlatitudes

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where the ice crystal is necessary for the precipitation process to work effectively.

In 1946 Vincent J. Schaefer (6) discovered that small bits of dry ice particles dusted into a supercooled cloud would quickly and completely change its nature. In 1947, Dr. Bernard Vonnegut (7), an associate of Schaefer and Langmuir, discovered that silver iodide would do the same thing (convert supercooled clouds into ice crystals). It was these discoveries that started the tremendous worldwide interest in atmospheric physics and experimental meteorology in progress the last 13 years. It also brought into being a large number of commercial cloud seeding companies that would "make it rain." Later this expression was changed to "increase rainfall for a price." It has been estimated that during this period of extreme optimism over 500 cloud-seeding projects were undertaken both in the United States and foreign countries. By the early 1950's some $3 million to $5 million were paid annually by farmers and waterpower companies to commercial cloud seeders.

Some 150 projects were conducted in foreign countries, mainly Canada, Australia, Holland, Switzerland, Spain, Japan, England, and France. Some 50 countries in all have reported work in this field.

So we find a great deal of basic and applied research being conducted in the United States and abroad, both by public and private agencies. All of these activities will add to the store of our knowledge, which eventually will give a definite answer to the hopes and expectations stemming from the discovery of Dr. Vincent J. Schaefer.

HOW DOES WEATHER MODIFICATION WORK?

"The possibility of causing rain to fall prematurely, or of augmenting naturally formed rain, hinges upon the fact that water vapor requires a nucleus of solid matter about which to freeze at temperatures warmer than −40° F." (Frederic A. Berry) (15). These freezing nuclei are quite variable in their behavior. Their numbers may vary a thousandfold or more, from day to day, and from place to place. Sometimes, apparently, there are too few to accommodate all the water vapor molecules which might otherwise become ice crystals. Moreover, they are unable to serve as freezing nuclei until the temperature has fallen to some value much colder than freezing. The specific value depends upon the composition of the individual nucleus, but in general, temperatures of 5° F. or colder are required for most natural nuclei. Weather modification as currently practiced, depends primarily upon the use of a substance (such as silver iodide) which will be effective as a freezing nucleus at temperatures warmer than those required by natural occurring nuclei.

THE ADVISORY COMMITTEE ON WEATHER CONTROL

The Advisory Committee on Weather Control was established by an act of Congress in 1953. The Committee was not authorized to conduct basic research in weather modification but was directed to make "a complete study and evaluation of public and private experiments in weather control for the purposes of determining the extent to which the United States should experiment with, engage in or regulate activities designed to control weather activities." The Committee's study of cloud seeding consisted of two major programs: (1) A statistical evaluation program, in which data from commercial cloud seeding operations were analyzed by mathematical methods to see if these operations actually had produced an identifiable increase in rainfall. (2) A physical evaluation program, to find out as much as possible by direct and indirect observation, what takes place in clouds when silver iodide crystals are released at the ground and from aircraft.

The Committee's final report, volumes I and II (23), issued December 31, 1957, is the most authentic and complete report on weather modification in existence today. A great deal of information as to the possibilities of increasing rainfall and hence the water supply is contained in this report. It is for this reason some of the more important work and results of the Committee's activities and findings appears in this analysis.

The statistical group of the Advisory Committee made some valuable contributions in the areas of (1) the selection and development of statistical methods for better analyses of commercial cloud seeding data; (2) the application of these methods to the evaluation of enormous quantities of information on cloud seeding operations. The Committee had for its evaluation studies a larger and more varied collection of

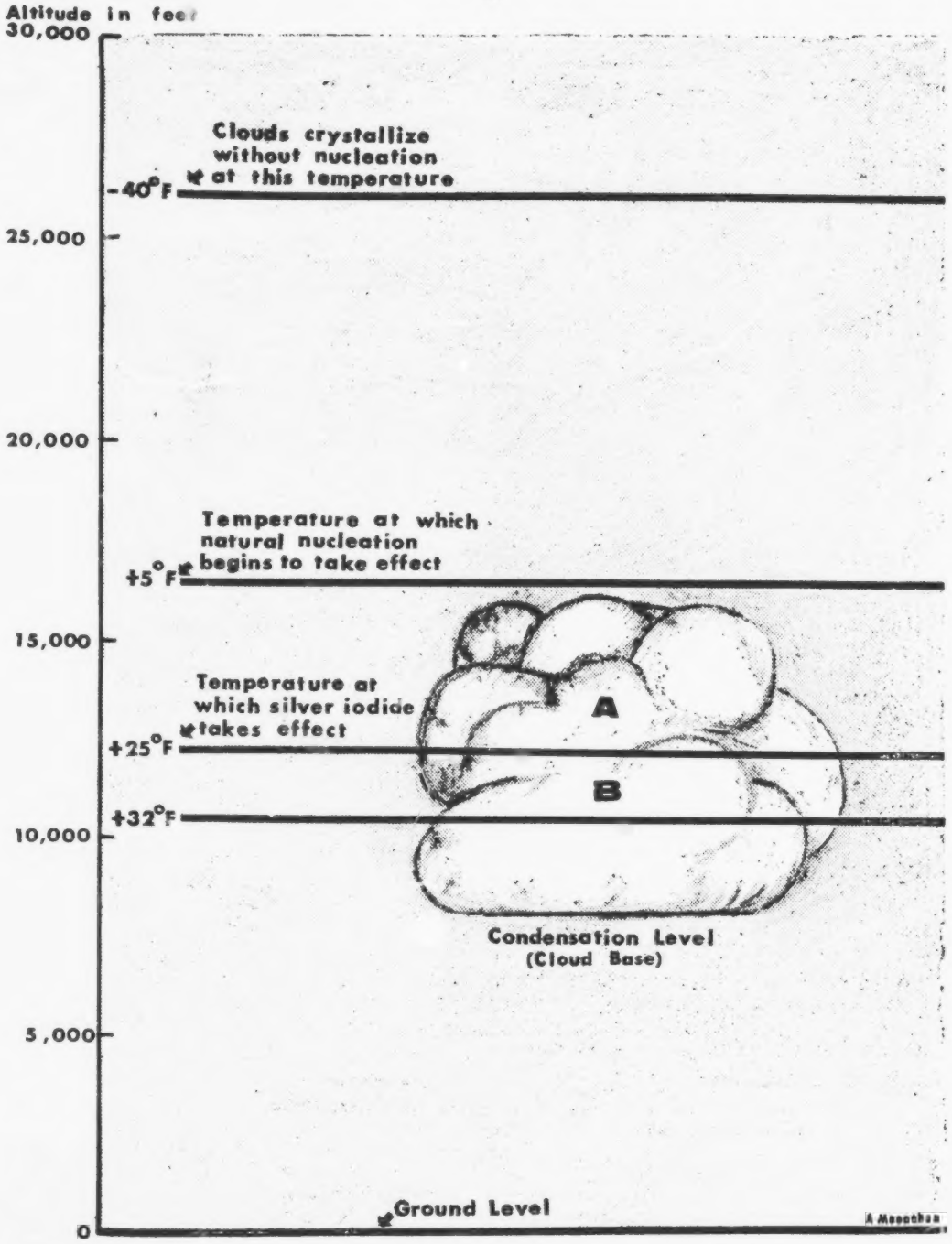

CHART 1 The theoretical effect of artificial nucleation of a cloud which has not reached the level of natural nucleation is shown. Water content of Zone A can be affected by silver iodide nucleation, while that of Zone B is unaffected by nucleation.

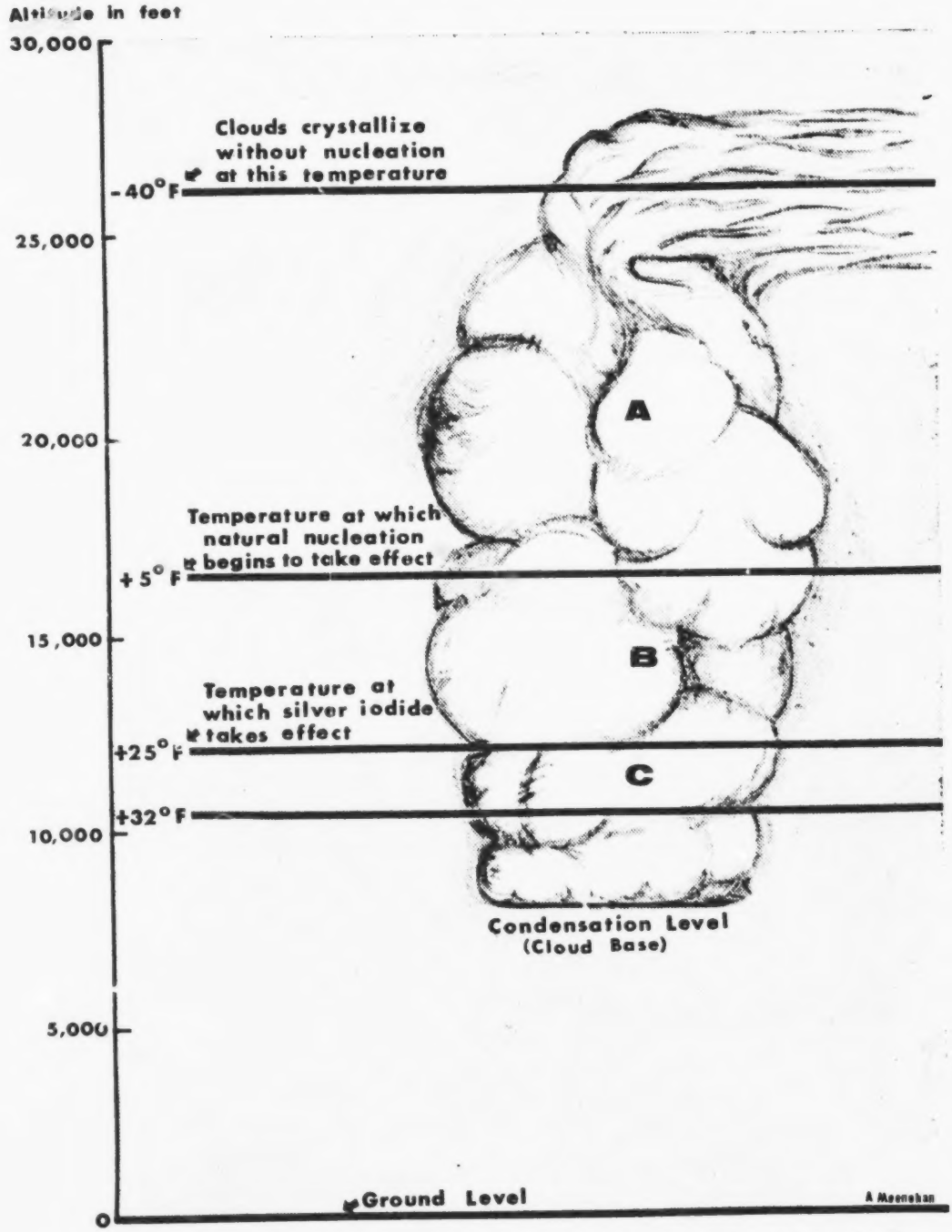

CHART 2 The theoretical effect of artificial nucleation of a cloud which has reached the level of natural nucleation is shown. Water content of Zone A can be affected by natural nucleation; that of Zone B, by silver iodide nucleation. Zone C is unaffected by nucleation.

information on cloud seeding operations than had ever been assembled by any group for study. Of all the available cloud seeding data furnished by private commercial seeders, 12 projects were selected because the data, from the standpoint of quality, were the most suitable for the contemplated analysis. The purpose was to determine, if possible, as to whether or not rainfall was increased because of the seeding of clouds. If successful this type of program would certainly be one way of increasing water supply. The study involved some 427 storms that were seeded to increase the rainfall. These seeded storms were analyzed for seeding effect on the basis of measured rainfall of 5,516 unseeded storms which occurred at the project sites during previous years, some going back a quarter of a century. Eleven of the projects were conducted in the United States and one in France. In 10 of the United States projects the unit of measurement was the rain falling in a special area during the passage of a storm. In the other project, stream discharge was used. In the French project, the total seasonal rainfall was used as the standard of measurement.

The U.S. Weather Bureau and Geological Survey furnished the precipitation and runoff data for the U.S. projects, the French Government, the data for the French project. The operators supplied the specific hours of operation for each generator, their exact location, the type of nucleant used on each occasion, and a description of the target boundaries. The Committee studied the history of each rain gage, so as to maintain the high quality of the data and for any indication of shift of location or for any environmental change, such as the growth of vegetation or the erection of buildings.

The effectiveness of cloud seeding is determined by the difference between what rainfall actually occurred after the storm clouds were seeded and what would have occurred had they not been seeded. To accurately determine the amount of rainfall that would have fallen from the unseeded clouds is impossible. A more reliable method is to compare rainfall on the target area with the rainfall on a control area which is a nearby area assumed to have similar rainfall under natural conditions.

The potential effectiveness of cloud seeding is greatly influenced by the presence of or absence of mountain ranges in the area, so the projects were divided into three classes:

1. The orographic class: In orographic areas the updrafts created by the land barriers help lift the artificial nuclei to effective heights, making these areas ideal for cloud seeding.

2. The semiorographic class: This includes less mountainous areas, where land barriers are less useful in aiding the lifting of artificial nuclei into the clouds.

3. Nonorographic class: This includes areas where land barriers do not exist. If they do, they cannot be expected to lift artificial nuclei aloft.

The conclusions of the committee are significant and should have a great bearing on the subject under discussion.

The committee concluded, for the orographic and semiorographic projects (all on the west coast) the evidence indicates that cloud seeding has produced an average increase of 10 to 15 percent in the precipitation from seeded storms. For the nonorographic projects (areas where land barriers do not exist) using the same testing methods, any change in precipitation could not be attributed to cloud seeding. The fact that no increase was detected does not mean that there was no increase. The increase may have been so slight that it could not be measured by the statistical methods used. This may have been the reason why the South Dakota project did not show a positive result from a study of the 41 seeded storms analyzed.

The South Dakota project is mentioned here because at the height of its cloud-seeding activities by private seeders, some 12 million acres were under contract.

In the particular farming area involved in the project, any increase in rainfall would be significant. The method of evaluation used by the committee when applied to the data showed no perceptible increase due to seeding. Workers at South Dakota State College using the same data came up with an increase of 8 percent. Much of this increase was due to two of the storms. It cannot be said that cloud seeding was not effective. Visual observations and opinions of farmers who were interviewed said they were convinced that cloud seeding did increase rainfall in their area.

In no instance was it said that cloud seeding had produced a negative effect.

In seeking to discover the effectiveness of cloud seeding from data furnished in the 6 years prior to the existence of the committee, it had to rely on various assumptions which presume that our scientific knowledge is adequate to interpret the available data at hand. The results of the study of the data furnished for those years, showed a definite, positive reaction occurring in the seeded areas when compared to adjacent areas not seeded. Data assembled for a period of a year or two could very easily be misinterpreted because of the wide variations which occur in natural precipitation. When, however, positive effects persist for longer periods, it seems that it should justify one to take a more optimistic view of the effectiveness of cloud seeding.

Along with the data furnished by private operators it was felt that independent data on the behavior in the atmosphere of silver iodide particles in plumes sent out by ground-base generators should be secured by the committee. This resulted in setting up what was called Project Overseed.

Project Overseed.—This cloud-seeding project was conducted around Mount Washington in New Hampshire. Silver iodide ground generators were used, the same kind that were used by cloud seeders in the West. Studies were made of the silver iodide plumes under various weather conditions. The presence of silver iodide at the summit of the mountain was studied. They established with reasonable certainty that silver iodide from ground generators retained its effectiveness to cause noticeable changes in supercooled clouds at least 10 miles from the generator location.

Project Sailplane.—This project was conducted in the Northwest, and its object was to determine if silver iodide from ground generators under summertime conditions, and under bright sunlight, would lose its activity due to deactivation. The work took place near Missoula, Mont. The plumes were explored by using a sailplane carrying a pilot and an observer. It was equipped with a portable cold box. Concentrations of silver iodide particles were detected, which despite the bright sunshine were of sufficient quantities to allow for very little deactivation of silver iodide particles during its movement from ground to elevations up to 4,500 feet.

Project Skyfire.—During 1956, studies were made of the effectiveness of silver iodide ground generators, in the plateau region of Arizona and the San Francisco Peaks near Flagstaff, Ariz. Silver iodide was emitted during thunderstorms. This was a cooperative study between the U.S. Forest Service, the Munitalp Foundation, the U.S. Weather Bureau, and the Advisory Committee. These studies were of great value and much was learned about the problems of determining effects of ground generators. Based on these findings, the field group moved to Missoula, Mont., in July and inaugurated a series of cloud surveys and cloud-seeding studies of mountain cumulus in the Bitterroot Mountains of western Montana. These studies again demonstrated that if deactivation of silver iodide occurred it was not severe enough to prevent striking glaciation effects in clouds supercooled to −5° C. or colder. Project Skyfire was continued in 1957. The studies again demonstrated that the deactivation of silver iodide is not as serious as has been suggested by some investigators.

Project Seabreeze, 1956.—This project was conducted in Florida and continued the exploration of the behavior of silver iodide plumes, the growth of cumulus clouds, and the role played by ice nuclei in clouds formed by the sea breeze along the east coast. It was found that warm cloud rain invariably occurred before any seeded precipitation could start, making the analysis of seeding results especially difficult.

Project Seabreeze, 1957.—Based on field experiences of the previous 2 years was developed and the precipitation reactions occurring in them. These were tested at Boca Raton and Mount Withington. This type of work is of fundamental importance in the understanding of the possibilities and limitations of cloud-seeding activities and illustrates one type of study which must be continued and expanded.

The Santa Barbara project was another study designed to assist in securing a better understanding of west coast storm precipitation. This too is a cooperative project in which the major cooperators are the county of Santa Barbara, the National Science Foundation, the Statistical Laboratory of the University of California, the California Department of Water Resources, the U.S. Weather Bureau, the U.S. Forest Service, and the Advisory Committee. It is to run for a period of 3 years.

The projects discussed above were a series of inexpensive ones and yielded information of basic importance to atmospheric physics and at the same time permitted the Committee on Evaluation to proceed in their task with a reasonable degree of assurance that the effects evaluated had a strong likelihood of representing more than just the random fluctuations of completely natural precipitation.

STATEMENT OF POLICY ON WEATHER MODIFICATION [1]

1. The seeding of supercooled cloud with dry ice will usually convert at least a portion of the cloud to ice crystals. Under appropriate conditions such seeding may release variable amounts of precipitation from fairly deep and active cumulus clouds in which the natural release of precipitation has not already started. Small, active cumulus clouds are usually dissipated when they are seeded with dry ice. Holes or valleys may be produced in supercooled layer clouds or supercooled fogs by seeding them with dry ice.

2. The injection of waterdrops on hygroscopic salt particles into active, warm (nonsupercooled) cumulus clouds may release some rain. Small inactive, warm cumulus clouds may often be partially or completely dissipated by seeding them from above with waterdrops or other particles; such dissipation may occasionally be accompained by the release of very light rain.

3. In some cases warm fog and stratus may be dissipated in restricted regions by the use of certain hygroscopic materials.

4. At temperatures below about minus 5° C. silver iodide crystals are known to affect supercooled clouds in much the same way as dry ice. The frequent absence of clear-cut results following the operation of ground-based silver iodide generators is believed to be due to one or more of the following causes: (*a*) The failure of the seeding material to reach the supercooled clouds; (*b*) the absence of clouds that could be affected by seeding; (*c*) the decay of the silver iodide; (*d*) the presence of an ample supply of natural ice crystals; (*e*) topographical influences which defy quantitative measurement.

5. Cloud seeding acts only to trigger the release of precipitation from existing clouds. The release of substantial amounts of precipitation by either natural or artificial means requires the preexistence of an extensive moisture supply in the form of moist air currents and of active cloud-forming processes. For this reason the meteorological conditions most favorable for the artificial release of precipitation are very much the same as those which usually lead to the natural release of precipitation. This factor plus the extreme natural variability of precipitation makes the evaluation of the effects of seeding difficult and often inconclusive.

6. Evaluations performed by independent agencies have yielded reasonably convincing evidence of increases of precipitation due to the operation of ground-based iodide generators only for operations conducted in cold weather in regions where forced lifting of the air over a mountain range is an important factor. No convincing evidence has been presented which indicates that ground-based iodide seeding affects the amount or character of the precipitation over flat country. This does not prove that there are no such effects but suggests that if present they are too small to be detected by statistical analyses of data available to this date.

7. In the absence of a truly quantitative theory of precipitation the best present means for obtaining a quantitative estimate of the effect of seeding on precipitation is through the statistical evaluation of randomized cloud seeding experiments. The randomization is necessary to insure valid interpretation of the results and a long series of such experiments may be necessary to detect small effects.

8. Present knowledge of atmospheric processes offers no real basis for the belief that the weather or climate of a large portion of the country can be significantly modified by cloud seeding. It is not intended to rule out the possibility of large-scale modifications of the weather at some future time, but it is believed that if possible at all, this will require methods that alter the large scale atmospheric circulations, possibly through changes in the radiation balance.

9. All cloud seeding operations should be considered as experiments since the techniques are still under development and there is no sound basis for the quantitative estimation of the results

[1] Issued by the American Meteorological Society, Apr. 30, 1957. This statement by the society supports the findings of the Advisory Committee on Weather Control.

in advance of the operation. As experiments they should be designed primarily to yield optimum scientific results. There is good reason to believe that improved returns from cloud seeding will result from a sound experimental approach and this should be fostered by all concerned.

WHAT SOME SCIENTISTS ARE SAYING

Batton and Kassander (12) concluded after two summers of work in cooperation with the University of Chicago in seeding orographic cumuli clouds that the tests discussed were incapable of showing with statistical significance that seeding caused an increase in rainfall. They suggested, however, that increases were produced and that further tests were to be made.

In 1958 and 1959, Batton and Kassander (12) conducted the cloud seeding program in connection with the University of Arizona. It was directed toward the study of the effects of silver iodide nuclei on supercooled orographic cumuli. Clouds over the Santa Catalina Mountains were studied. The procedure involved an objective prediction, made prior to 0900 MST each day, as to whether or not cumulus congestus or cumulonimbus clouds would form over the Santa Catalina Mountains. The actual seeding was carried out with an Australian type airborne silver iodide generator placed on the underwing of a Supercub airplane.

The experiments conducted during the first 2 years suggest that silver iodide caused some important changes in the natural cloud processes. When data from both years were combined it was found that the mean rainfall per gage was 30 percent higher on the seeded days. The probability that observed differences in the mean rainfall occurred by chance was quite high, about 0.14. A comparison of the extreme rainfalls on seeded and nonseeded days showed greater differences, but the statistical confidence of real difference was still not sufficiently high to be acceptable.

This research is still in progress so the authors do not feel that they are ready to draw final conclusions. Although the results to date point toward the conclusion that seeding produced important effects, it is vital that more data be compiled in order to be sure that the results have not been brought about by chance.

In the report "Cloud Physics and Rainmaking" (1) the University of Chicago gives this fair appraisal.

The enthusiasm with which discoveries of rainmaking possibilities have been received may lead the casual observer to say that weather control is an established fact that needs only proper application. Most meteorologists would say that there is only limited usefulness of present techniques and would take a cautious but optimistic stand. There is a vocal minority of meteorologists and other scientists who are satisfied that large scale production of striking increases in rainfall has been proved and who are impatient with those who ask for better proof. At the other extreme there may be a few who would say that rainmaking is not worth trying.

The British Meteorological Office (14), 1957, has this to say:

Theoretical ideas and practical experiments (mainly conducted in other countries) on the intriguing problem of artificial "rainmaking" have been closely studied only to confirm th view that there is no ground for optimism except perhaps where clouds frequently form over mountains higher than exist in the British Isles. Meanwhile our own experiments with the release of silver iodide from ground generators on Salsbury Plain continue as opportunity offers with no result yet detectable.

F. A. Berry (15) states that a few years ago people were enthusiastic about the potentials of cloud seeding and expected fantastic results. Now this same group still has the enthusiasm but are somewhat restrained by a better understanding of the many limitations that exist. He makes the following observations:

(1) That cloud seeding is not a cure-all for drought. It is not possible to make rainfall whenever and wherever it is desired, but rather to affect weather conditions when and where they occur naturally.

(2) Cloud seeding is not a substitute for water storage and irrigation. Indeed, it would seem to make these factors more important. To exploit fully any additional precipitation obtained, it must be possible to store it when and where it falls and transport it where it is needed, when it is wanted.

(2) The average increase obtainable in the most favorable circumstances appears to be about 10 to 15 percent rather than 50 to 100 percent that was being estimated by some people a few years ago. These amounts may be increased slightly by improved engineering practices and modest as they are, may nevertheless be of considerable importance in a wide variety of circumstances. The actual economic benefit in each particular case must be determined on its own merits.

H. G. Houghton (18) has this to say:

One can be quite confident that the ultimate success of methods for the artificial release and control of precipitation will depend on the acquisition of much more complete basic knowledge of the ways in which nature produces rain and snow. Present attempts at rainmaking are often uncomfortably close to "shooting in the dark." This is not to say that nothing has been learned from or accom-

plished by these effects, but simply that the effective control of any mechanism demands much more complete information than is now available on natural precipitation.

Trials of this type have been carried out on a large scale during the past 6 years, mainly in the United States by commercial operators. The results are the subject of much controversy; unfortunately, judgment has often been clouded by arguments of intuitive or emotional nature, when critical appraisal of the results at this stage appear inconclusive. From the published data one can find no convincing evidence that very large increases in rainfall can be produced consistently over large areas, although there is some evidence to suggest that under favorable conditions marginal effects of 10 to 20 percent may be produced. In general the operations have not been continued for a sufficiently long period of time and have not been designed for use with evaluation techniques sufficiently sensitive to separate effects of this magnitude from the natural variations in rainfalls. Certainly many of the spectacular claims made on the base of very short periods cannot be justified.

Capt. Howard T. Orville, U.S. Army (retired), (26) Chairman of the Advisory Committee on Control, when it was in existence and now vice president, Beckman and Whitley, Inc., San Carlos, Calif., has written many papers on the possibility of increasing the water supply through the seeding of clouds. The following is taken from his article "Stand By for Climate Control" (25) appearing in the Saturday Evening Post:

> Some of our Government sponsored weather projects are kept secret because they involve national defense, but others, such as the seeding of clouds to produce rain, are usually in the hands of commercial companies. Modern scientific attempts to increase rainfall usually are dated from experiments by August V. Veraart in Holland in 1930, but such efforts were often greeted with skepticism and sometimes with ridicule for the next 20 years, even after D. Irving Langmeier and Dr. Vincent J. Schaefer made important discoveries in the field in 1946. Then Dr. Bernard Vonnegut found that microscopic silver iodide crystals, really silver iodide smoke produced by generators, were most effective in seeding clouds. This resulted in greater interest by our Government and several projects were established. By the early 1950's from $3 million to $5 million were paid annually by farmers and water-power companies to commercial cloud-seeding concerns in an effort to increase rainfall, mostly in the Western States.
>
> There is no question in my mind that the seeding of clouds, which was ridiculed by many scientists only a few years ago, has been proved effective, within limitations, to increase rainfall.
>
> In experiments in New Mexico, rockets have been used to spend chemicals that changed the composition of the upper atmosphere. Successful developments of the ability to alter the atmosphere could lead to far-reaching climate modification and theoretically could free the Plains States of drought.

Dr. Joseph Kaplan (27), head of the U.S. Committee for the International Geophysical Year has said that

> Control by man of the earth's weather and temperature is within the realm of practicality now.

Dr. Roscoe R. Braham, Jr. (28), with the Institute of Atmospheric Physics, University of Arizona, states that a systematic study of clouds is a prerequisite to cloud modification experiments.

The Department of Meteorology, University of Chicago, 1958 (1), reported:

"Although considerable effort has been made by the Weather Bureau and New York University researchers (ACA projects) at this time there is no acceptable evidence that one can modify large cloud systems and the weather pattern which they accompany. This does not mean that such effects are not possible, it only reflects that the natural variability in these storms is so large, and our techniques so crude, we have not been able to find the effects if they exist."

The Quarterly Journal of the Royal Meteorological Society, April 1955 (51) has this to say:

> It has been shown beyond all reasonable doubt, particularly by Bowen's group in Australia, that cumulus clouds in a suitable state of development can be induced to release showers by seeding them with dry ice, when similar unseeded clouds in the vicinity do not precipitate. This type of experiment is, however, not likely to tell us very much about the possibilities of modifying the rainfall from widespread cloud systems extending over large areas.
>
> For experiments of this scale it becomes uneconomic to disperse the seeding agent from aircraft and the general practice is to release silver iodide in the form of smoke from the ground, relying on the air currents to carry it up into the supercooled regions of the cloud mass.

Richard G. Semonen (36) in his work on artificial precipitation potential during dry periods in Illinois summed it up by stating that much more research is needed before definite conclusions can be reached. In his work the macroscale meteorological conditions of the atmosphere were studied during 31 dry periods which occurred in 1953–55.

A dry period is defined as at least 5 consecutive days with less than 10 percent of the normal precipitation over an area in east central Illinois. The parameters investigated measured at Rantoul, Ill., were, precipitable water, low cloudiness and Showalter stability index. The upper airflow, surface temperature, and general synoptic conditions were considered in individual case studies. The results show that although there is near normal water vapor in the atmosphere during majority of the dry periods, there was a deficit in low clouds. It is concluded in the study that in addition to present cloud seeding techniques, much research is needed to determine means of initiating clouds, since during dry periods in Illinois, a large quantity of clouds desired for seeding are not available.

Sänger (20) of Switzerland in studying the structure of ice-forming nuclei reports his findings show that the ice nucleability of substances does not essentially depend on their macroscopic structure or symmetry.

H. G. H. Ligda (21) of Texas A. & M. stated:

> Now there are evidently two things which cloud seeding can accomplish: It can initiate rain where Mother Nature is not going to do the process itself, or perhaps anticipate her in the formation of rain. The second thing we can do with cloud seeding is to perhaps either produce more rain or different form of rain where something is already going on by virtue of Mother Nature.

Vance E. Moyer (22) of the University of Texas, has this to say:

> There is no reason for us to stay in the laboratory for say 6 years getting a lot of statistics before we can start field experiments that, I feel will produce rain for farmers that need it, and at the same time help us in our work. It may be years before we learn all we want to know about pure research. In the meantime, there are some field experiments we could run that would help everyone.

In the September 1958 issue (24) of the American Meteorological Society we find this statement:

> The fears which the recent developments in nuclear energy and missiles have instilled in some have not completely stifled the feeling and pride of man's sudden access to energies and vehicles of magnitude and capability undreamed of a generation ago. This has led some to believe that the beneficial control of weather is around the corner and that all we have to do is to produce bigger bangs and higher, faster vehicles to achieve this desired goal. But something more than this is needed. We must know where and how to apply the energies available to us in order to bring about the desired results. To do this we must know more about what makes the atmosphere behave the way it does.

Irving P. Krick and his associates reported to the Southwest section meeting of the National Meteorology Society meeting in 1955 (9) that during the past 6 years his company conducted broad scale cloud seeding operations in 23 States and 10 foreign countries. The operational time logged for these operations amounted to over 400,000 generator-hours.

Dallas, Tex., project.—"Object was to increase municipal water supplies. The total increase for the years 1953, 1954, and 1955 was 212,950 acre-feet. During the period 16 good operational storms were seeded which reflected 40 percent increase in rainfall when the Dallas shed was compared with adjacent drainage basins. It can be assumed that the 40 percent increase in rainfall also accounted for a 40 percent increase in runoff over the same period. If the amounts of runoff for these 16 storms were accumulated, it would amount to 212,950 acre-feet."

Oklahoma City project.—"At the end of the period of operation (November 1953–May 1954) the city received roughly 47,000 acre-feet of water, compared to 24,000 acre-feet during the similar period in 1953 when no cloud seeding operations took place. The average percentage of normal precipitation over the watershed area was approximately 130 percent compared to areas outside the influence of cloud seeding with an average of about 80 percent."

Springfield, Mo. project.—"At the beginning of operation, Lake McDaniel, the main source of the city's water supply, was about one-ninth of its capacity filled, some 165 million gallons. As a result of the seeding operation Lake McDaniel was filled to overflowing in less than a year's time."

Shreveport, La., project.—"In January 1955 the water in Cross Lake, the city's reservoir, was at a dangerously low level. The years 1953 and 1954 had been extremely dry. The city signed a contract for rain increasing in January of 1955. When the seeding started the lake contained about 9 to 10 billion gallons. By March 20, 1955, the water in the lake had risen to 18 inches above the flow line. By April 15 it reached 24 inches and by May 23, 36 inches above the flow line. If only 25 percent of the total increase in water could be attributed to cloud seeding, it still amounts to about 10,000 acre-feet of water, which would account for an income of over $1 million."

Mr. Paul E. Ruch (30), vice president of the

Water Resources Development Corp., points out that in their work in the wheatlands of eastern Washington, it has been shown that those areas for which weather modification operations have been conducted for 5 successive years have obtained from 6 to 14 inches more rainfall than adjacent nonoperated areas. Three years of operations over the Alberche River watershed in Spain, to increase streamflow for hydroelectric power production, resulted in an average of 55 percent above expectancy. He sums up his paper with some very pertinent statements.

1. The weather engineer can increase the amount of precipitation that would fall naturally.

2. In cloud-seeding projects that we have operated for a minimum of 5 years, total precipitation over the target areas is ranging generally from 10 to 30 percent above precipitation in adjacent nonoperated areas.

3. The success of a cloud-seeding program depends on the equipment used and the skill of the weather engineer who directs the operations. It is not an exact science and the skill of the weather engineer is a controlling factor in determining the success of the operation.

In a cloud-seeding program the amount of additional moisture obtainable will depend largely on the climatic conditions of the target area. In regions where storms produce large amounts of precipitation, weather modification operations can produce larger increases than in those regions where normal amounts of rainfall are smaller.

Wallace E. Howell (49) reports: "York County, Pa., 1954, an increase of 18 percent, significant at 5 percent level."

South Carolina, 1954, interim evaluation covering last 4 months, 43 percent, significant at better than 1 percent.

"United Fruit, 1953, an increase of 18 percent regression analysis gave a good correlation between target and control, result significant at better than 1 percent level."

Mobile, Ala., 1954, interim evaluation covering last 4months of 1954, some water spray seeding included showed increase of 37 percent, significant at 5 percent level.

Ralph D. Kline (46), of the U.S. Weather Bureau, in a paper presented before the Missouri Basin Inter-Agency Committee in March of 1957, made the statement that the discovery in recent years, that cloud seeding does modify some clouds under certain conditions, has placed the subject into the realm of serious scientific and engineering interest. "The practical question is now one, not so much of whether cloud modification is possible, but rather when, where, how often, and how well does it work in terms of altering cloud performance." The paper reviews the cooperative work of the Weather Bureau, Department of Defense, the National Science Foundation, Department of the Interior, Department of Agriculture, the National Advisory Committee for Aeronautics, and, since 1953, the Advisory Committee on Weather Control. Soon after the first experiments of Drs. Langmuir and Schaefer, the Weather Bureau in cooperation with other Federal agencies, began plans for a seeding test program. During 1948 and 1949 nearly 200 seeding operations were carried out over Ohio, California, and the Gulf Coast States.

Mr. Kline had this to say about the results of these test programs:

Consideration of these and other factors lead to the hypothesis in 1949 that cloud seeding had the greatest likelihood of success under orographic conditions where supercooled clouds might form and remain relatively stationary with respect to the terrain for extended periods of time.

In 1950 the Weather Bureau turned its attention to a 3-year cooperative evaluation project of a seeding operation being conducted over the Bishop Creek watershed by the California Electric Power Co. The results were indicative of increases in runoff of about 10 percent, although uncertainties were encountered due to unusual weather conditions that prevailed during 1 year of the 3-year period. Most of the statistically estimated increases occurred during this particular winter and inconsistencies in snowpack and direct snowfall measurements were detected.

In 1952 another large coordinated Government field experimental program was undertaken by the Weather Bureau, Army, Navy, and Air Force. The essential conclusions were that no effects were discernible (dry ice seeding by aircraft and silver iodide from ground generators). In the words of the evaluators:

If seeding had any effect on the large-scale precipitation or on the pressure field, it was too small to be detected against the background of natural meteorological variance.

The paper concludes with this statement:

My purpose today has been essentially one of explaining frankly, and as fully as time has allowed, some of the many facets and problems of the cloud modification field. There are many other equally fascinating facts which may turn out to be important. I have taken the point of view that

perhaps the best way of telling you where we are at the present time is to give you some idea of where we have been. Others, I am sure will take a much different approach. Final conclusions are not yet possible, although some promising and other not so promising clues have been uncovered. Taking a very realistic point of view, I think the evidence is converging toward the view that the immediate possibilities are less promising than most of us had hoped. The favorable evidence to date urgently requires further checking, engineering development, and documentation, particularly on physical grounds, but also by more vigorous statistical techniques.

ECONOMIC IMPLICATIONS

In several of the papers reviewed as to the possibility of increasing the water supply through weather modification (rainfall) the economic feasibility was questioned. The Advisory Committee on Weather Control appointed a subcommittee to study this phase of the problem and the following are excerpts from their report:

A paper prepared by the California Division of Water Resources (52) has this to say:

> A study of the effects of a 10-percent increase in precipitation on an irrigated area in California showed the following results:
>
> 1. Average annual streamflow increased by 15 percent.
> 2. Streamflow in minimum year of record increased 28 percent.
> 3. Average potential yield of stream increased by 15 percent.
> 4. Firm yield of existing facilities increased by 10 percent.
> 5. Irrigated area increased by 10 percent with resulting total annual benefit of about $1,125,000.
> 6. Increase in firm power production with annual value of $50,000.

Another study which is described in the same paper, deals with the economic effect of 10 percent additional rainfall in the northern Great Plains States of North Dakota, South Dakota, and Nebraska. The effects of the increase in rainfall were explored by considering the relationships existing between average annual precipitation and per acre farm value and average size of farms, as given in the 1950 census. For the three northern Great Plains States of North Dakota, South Dakota, and Nebraska, the study indicated that there apparently would be an increase of 35, 70, and 46 percent, respectively, in the per acre farm value of the three States and an increase of 20, 54, and 18 percent in the number of farms.

In the Great Plains a considerable number of studies have indicated that, in the case of spring wheat, 1 inch of precipitation, above 5 to 10 inches, is associated with a yield increase of 1.5 to 3.5 bushels per acre. If we assume that the ratio of increase in yield to increase in precipitation is 2 to 1 over a base of a minimum of 8 inches, about 1 inch of rainfall will yield 2 bushels of wheat. The 4 million acres of wheat in South Dakota, assuming wheat at $2 per bushel, represents an annual total increase in gross income from wheat of $24 million. Cloud seeding at 5 cents an acre would cost $200,000, leaving a net increase in income of $23,800,000.

Increased precipitation through cloud seeding would have a large effect on increasing hydroelectric power production. Assuming that a 20 percent increase in precipitation will result in an average 25 percent increase in runoff, it would mean an annual increase of 64,000 acre-feet, of which 31,000 acre-feet, or 48 percent, could be utilized to produce hydroelectric power and the remainder would be spilled.

Increases of agricultural production and power production would also mean an increase in the volume of other businesses.

The report concludes by stating that a 10 percent increase in precipitation would be worth at least $300 million annually to the Missouri Basin in terms of agriculture and power. The value of greater increases in precipitation and of other weather modifications which would temper the harsh climate to permit more certain production, would be even greater.

Richard G. Semonen (36) in his study of artificial precipitation potential during dry periods in Illinois summarizes an attempt to examine some of the more obvious macroscale parameters of the environmental atmosphere, such as precipitation water, low cloudiness, and stability during periods when artificial stimulation of precipitation is most needed; that is, during periods when the natural precipitation process is either not functioning or is very inefficient.

The study has brought to light some of the interesting features of the conditions of the large scale atmosphere during periods of little or no precipitation in the Midwest. The study is presently in its initial stages and will be developed more fully, but the preliminary results present

some interesting aspects of the problem of weather control. If we are to alleviate drought in the agricultural areas of the Midwest, it appears that in addition to seeding existing clouds to increase precipitation, methods for initiating clouds must be developed. If Illinois is considered representative of the Midwest, a large quantity of clouds desired for seeding are just not available during dry periods.

CONCLUSIONS AND RECOMMENDATIONS

Howard T. Orville, vice president, Beckman and Whitley, Inc., in his article on "The Effects of Weather Modification on Water Supplies" concludes as follows:

The beneficial effects of weather modification in augmenting our water supplies rests solely upon the extent of national interest in developing techniques that will make it possible to—

a. Substantially increase the snowpack in the western mountain regions.

b. Make effective use of moisture laden clouds in providing additional water to flatlands.

c. Relieve water shortages by substantial increases in precipitation in the watersheds of many municipalities where growing uses by industry have created water shortages.

d. To realize economic benefits of inestimable value to large areas of the United States if carefully designed experimentation with large-scale weather systems is carried out.

e. To prevent the formation of destructive hail and lightning producing storms after we have gained a much better understanding of precipitation processes.

f. To develop techniques for the suppression or diversion of destructive hurricanes, after carefully designed and controlled experimentation over a period of 10 to 15 years.

The cost of developing such an atmospheric research program would probably be less than that now being allocated for lunar probes, and much less than the $2 billion spent on the development of the atomic bomb.

Quotes from various scientific papers:

There is general agreement among scientists and others that positive effects can be secured and that precipitation can be increased under favorable circumstances, however, the limitations of the method, the quantitative results, and the prediction and control, are not at present known to any degree of certainty.

This new tool could have a profound influence on regional and national growth.

Data so far indicates cloud seeding can increase precipitation under orographic conditions 9 to 17 percent.

Weather modification offers an opportunity of increasing the volume of our water supply in many parts of the country.

In the United States conditions for seeding occur on the west coast. Further research may extend that to the flat lands and eastern sections of our country.

In increasing water supplies through cloud seeding and weather modification each area will have to be studied separately. Perhaps on a watershed basis. Large-scale seeding may have its effect on the total supply of water available in the United States but it will be localized.

In the future in planning water development a study should be made of the potentials of artificial cloud seeding by areas.

Not entirely dependable at present. Need to have sufficient moisture-laden air under the right atmospheric conditions to be successful. In periods of drought with very few clouds major increases unlikely.

Potentials and limitations of weather modification techniques not clear enough to permit long-range planning with any degree of satisfaction.

Both laboratory and field tests, with randomized choice of operational procedure, are needed.

Also information on types of atmospheric and geographic conditions suitable for cloud seeding, types of clouds that will react to modification, best materials and methods for seeding the clouds.

Seasonal distribution of additional precipitation.

Heat and lightning suppression.

Increase or decrease of precipitation downward from the target.

Evaluation of field results, will need extensive data on rainfall, snowfall, snowpack, snow moisture; content and runoff and data on all other weather variables.

Cloud seeding should be directed to actual use and to research rather than to research alone.

Cloud seeding may prove its value long before everything about it is known.

Must move out of the cold box and laboratory stage.

Atmosphere may do man's bidding after many years but people may still make fresh and exciting discoveries about the way the atmospheric system works.

RECOMMENDATION OF THE ADVISORY COMMITTEE ON WEATHER CONTROL

1. General

That encouragement be given for the widest possible competent research in meteorology and related fields. Such research should be undertaken by Government agencies, universities, industries, and other organizations.

That Government sponsor meteorological research more vigorously than at present. Adequate support is particularly needed to maintain continuity and reasonable stability for long-term projects.

That the administration of Government-sponsored research provide freedom and latitude for choosing methods and goals. Emphasis should be put on sponsoring talented men as well as their specific projects.

That an agency be designated to promote and support research in the needed fields, and to coordinate research projects. It should also constitute a central point for the assembly, evaluation, and dissemination of information. This agency should be the National Science Foundation.

That whenever a research project has the endorsement of the National Science Foundation and requires facilities to achieve its purpose, the agency having jurisdiction over such facilities should provide them.

2. Specific research.

The effect of solar disturbances on weather.

The factors which control our global atmospheric circulation.

The factors which govern the geneses and movement of large-scale storms.

The dynamic of cloud motions.

The processes of rain and snow formation, and the relative importance of the physical phenomena which govern these processes.

The electrification process in clouds and the role electricity plays in meteorological phenomena.

The natural sources of condensation and ice-forming nuclei and their role.

The methods, materials, and equipment employed in weather modification.

RECOMMENDATIONS AND SUMMARY BY A. M. EBERLE

I stated at the beginning of this report that I would present the discussion of weather modification as a means of increasing the water supply in lay language. I hope I have succeeded.

We have made great progress in the field of weather modification since 1946 when V. J. Schaefer first told the world of his laboratory experiments. Many of the skeptics at that time will today admit that the seeding of clouds under certain conditions will produce rain.

The "fly by night" private operators that took advantage of this discovery and went into the rainmaking business for a price have all disappeared. The sound, well qualified operator is still doing business. These exploiters did a lot of damage and gave rain increasing a bad name.

The present operators, seeding clouds for a price, know what they are doing. These operators are qualified meteorologists and in the course of their operations have made a great contribution to the advancement of cloud physics and cloud modification. One cannot ignore the some 750,000 hours of seeding experience that they have had. Surely the laboratory scientist should be able to gain a great deal from this experience. We need both the scientist who is doing the basic research in the laboratory and the scientist who is doing the applied research by taking the present available knowledge and putting it to work.

Basic research is very important and it is only through it that we will be able to learn about the atmosphere and how we might be able to manage it for the betterment of mankind. I earnestly plead with our Congress, the National Science Foundation, the Federal agencies interested in this field and others interested, to step up basic research. At the same time I plead with these same groups that they publish their findings as soon as possible and that they give them to qualified cloud seeders, so they can put them to work.

People should not be asked to wait for years until the last facts of a particular study are known. Many areas of the country need to put to work the findings as they become available. It would

mean a great deal in dollars and cents in many areas even if rainfall can be increased only an inch or less. It doesn't take much additional rain at the right time to increase crop production in practically all States in the middle section of the United States.

I appeal to all meteorologists, whether in the field of basic research or applied research, to work together, exchange information and experiences freely. If this can be done, weather modification as a means of increasing the water supply will be possible within the next 15 years.

REFERENCES CITED IN TEXT

For a complete bibliography of references see the report of the Advisory Committee on Weather Control, volume II.

1. University of Chicago, "Cloud Physics and Rainmaking," research programs of the University of Chicago, Department of Meteorology, 1957.
2. Humphreys, W. J., "Physics of the Air," McGraw Hill Co., 1940.
3. Langmuir, Irving, "Analysis of the Effect of Periodic Seeding of the Atmosphere With Silver Iodide," Part II—Final Project, Project Cirrus; G. E. Research Laboratoty Report No. RL–785, Schenectady, N. Y., May 1953.
4. Schaefer, V. J., "Laboratory, Field and Flight Experiments," Part I—Final Report, Project Cirrus, G. E. Research Laboratory Report No. RL–785, Schenectady, N.Y.
5. Schaefer, V. J., "The Production of Ice Crystals in a Cloud of Super-Cooled Water Droplets," 1946, Science, 104, pp. 57–459.
6. Schaefer, V. J., "The Formation of Ice Crystals in the Laboratory and the Atmosphere," Clem. Rev. 44, pp. 201–230.
7. Vonnugut, B., "The Nuclelation of Ice Formations by Silver Iodide."
8. Krick, Irving P., "Weather Modification and Its Value to Agriculture and Water Supply" J. of Royal Arts, Apr. 30, 1954.
9. Krick, Irving P., "Progress in Weather Control," Journal, AUWA, vol. 46, No. 8, August 1954.
10. Krick, Irving P., "Technical and Economic Aspects of Weather Modification in Relation to Water Supply," Journal of the Water Institute of England, vol. 8, No. 4, July 1954.
11. Batton, Louis J., and Kassander, A. Richard, "Randomized Seeding of Orographic Cumulus" 1957, Tech. Bull. 12, pt. I, University of Chicago, Department of Meteorology, Feb. 15, 1958.
12. Batton, Louis J., and Kassander, A. Richard, "Artificial Nucleation on Orographic Cumuli" University of Arizona, Institute of Atmospheric Physics.
13. University of Chicago, "Cloud Physics and Rain Making" Department of Meteorology, 1957.
14. The British Meteorology Office, annual report, year ending Mar. 30, 1957.
15. Berry, F. A., "The Evaluation of Weather Modification Experiments," Journal of American Waterworks Association, August 1956.
16. Berry, F. A., Vol. II—Final Report, Advisory Committee on Weather Control.
17. Houghton, H. G., "Cloud Physics" 1959, article, MIT.
18. Houghton, H. G., "An Appraisal of Cloud Seeding as a Means of Increasing Precipitation," Bull. 32, Am. Met. Soc., February 1951.
19. Semonen, Richard G., Illinois State Water Commission, Urbana, Ill., survey, May 13, 1959.
20. Sanger, Raymond, report, Federal Institute of Technology, Zurich, Switzerland.
21. Ligda, H. G. H., "Report" Houston Post, Aug. 19, 1956.
22. Moyer, Vance, "Alcade" November issue 1956, University of Texas.
23. Final Report, Advisory Committee of Weather Control, vols. I and II, Dec. 31, 1957, Government Printing Office.
24. American Meteorological Society, "Weather Research Projects," September 1958.
25. Orville, Howard, "Stand by for Climate Control," Saturday Evening Post, Nov. 29, 1958, pp. 19–24.
26. Orville, Howard, "The Effect of Weather Modification on Water Supplies."
27. Kaplan, Joseph, head of the U.S. Committee for the International Geophysical Year.
28. Brahm, Roscoe, Institute of Atmospheric Physics, Tucson, Ariz.
29. University of Chicago, "Modification of Hurricanes Through Seeding of Clouds."
30. Ruch, Paul E., "Implications of Weather Control," Winnipeg Real Estate Board, Feb. 2, 1956.
31. Reynols, R. R.; Sturm, M. D.; Warren, E. P.; "Cloud Seeding a Problem of National Importance," paper presented to Institute of Mathematical Statistics at East Lansing, Mich., September 1952.
32. American Institute of Aerological Research, "Analysis of Cloud Seeding Potentialities To Increase Natural Precipitation in Brule, Buffalo, Jerauld, Aurora Counties, S. Dak., Mimeographed Report No. 66, June 1951.
33. Thompson, John Eldon, "Estimating Commercial Expansion From Irrigation Development in the Oahe Unit Thesis."
34. Harmston, F. K., "The Multiplier as a Measure of the Indirect Benefit of Natural Resources Development," paper, Department of Commerce and In-

dustry, University of Wyoming, Cheyenne, Wyo., undated.

35. Bergeron, T., "On the Physics of Clouds and Precipitation," Pro. Fifth Assembly, WGGI, Lisbon, 1935.
36. Semonen, Richard G., "Artificial Precipitation Potential During Dry Periods in Illinois," Illinois State Water Survey, Urbana.
37. Krick, Irving P., "Results of Cloud Seeding Operations To Augment Municipal Water Supplies," Journal of American Water Works Association, vol. 48, No. 10, October 1956.
38. Krick, Irving P., "Rain Increase Projects in Relation to Water Resources," American Water Works Association, vol. 93, No. 11, November 1951.
39. Barrows, J. S., and others, "Project Skyfire," vol. II, final report of the Advisory Committee on Weather Control.
40. Boucher, Roland J., "Project Overseed," vol. II, Advisory Committee on Weather Control, pp. 127–136.
41. McCready, P. B.; Smith, J. B.; Dodd, C. J.; Bresmer, K. M.; "Nuclei, Cumulus, and Seedability Studies," vol. II, final report, Advisory Committee on Weather Control, pp. 137.
42. Final report, Advisory Committee on Weather Control, "Sea Breeze," pp. 158–161, "Mount Withington," pp. 161–163.
43. Schaefer, V. J., "The Economic Aspects of Experimental Meteorology Transactions," New York Academy of Science, Er. II, 12, June 1950.
44. Vonnugut, B., "Cloud Seeding," Scinetific American, January 1952.
45. Smith, E. J.; Hefferman, K. J.; Thompson, W. K.; "Tomorrow's Weather," Fortune 47, May 1953.
46. Kline, D. B., "Some Remarks on the Status and Results of Cloud Modification Research," U.S. Weather Bureau paper given at Missouri Basin Inter-Agency meeting, St. Joseph, Mo., Mar. 20, 1957.
47. Findeisen, R., "Selected Papers on the Physics Condensation and Precipitation," (MAB, 6H–126). Translated by A. R. Stickley.
48. Bowen, E. G., 1952, "A New Method of Stimulating Connective Clouds To Produce Rain and Hail," Royal Meteorological Society, Quarterly Journal 78 (335) 37–45.
49. Howell, W. E., and Associates, 1956, "Evaluation of the Cloud Seeding Program for the Cane Areas of Central Victoria, etc." September 1955–January 1956.
50. Mason, B. J., "The Natual and Artificial Production of Rain," Scientific Journal, Royal College of Science.
51. Royal Meteorology Society, Journal, April 1955.
52. State Water Resources Board, State of California, Division of Water Resources, Bull. 16.

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